Fuel Economy In Aviation

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Foreword

The pace of advances in aeronautical technology from the Wright brothers to today's supersonic military aircraft and jumbo jets has been rapid and the demands intense. Generally speaking, the driving forces have been the need for increased speed, range, and payload. All these factors have required major and continuous evolution in the technology of propulsion systems, structures, aerodynamics, and controls. In the almost 80 years since the first powered flight, there have been breakthroughs such as the monocoque fuselage, the all-metal airframe, the jet engine, the area rule and supercritical wing, and configurations that take maximum advantage of wing sweep. The present generation of subsonic transport aircraft has taken maximum advantage of these technologies as they were available at the time of design; thus, today's globe-girdling aircraft represent the state of aeronautical technology as it existed 10 to 15 years ago, when the decisions for development were made.

Throughout the course of the evolution of the modern subsonic transport and its military forebears, agencies of the U.S. Government have provided much of the expanded technology base reflected in today's state of the art. A principal agency has been the National Aeronautics and Space Administration (NASA) and its predecessor, the National Advisory Committee for Aeronautics. These organizations have striven to provide the major test facilities and professional expertise that have contributed much to the ability of American airframe and engine manufacturers to dominate the world's military and civil aviation.

With the advent of the global fuel crisis in the early 1970s, it became apparent that the continued utility and efficiency of U.S. aircraft could be severely affected by sharply rising fuel prices and potential shortages. Recognizing this situation, the U.S. Senate, in January 1975, requested NASA to develop a program for Aircraft Energy Efficiency (ACEE) which would as rapidly as possible develop new structural, engine, aerodynamic and control technologies for incorporation into future air transport industry designs. NASA responded with a program plan developed in conjunction with industry; Congress provided the funding, and the ACEE program was launched in 1976. This publication is an account of the origins of the program and its successes and the effects of the technologies developed on present and future aircraft. The ACEE program demonstrated that aircraft technology has not yet reached its peak and indicates avenues of research which, if vigorously pursued, may provide even greater technological advances in the future for all classes of aircraft.

William S. Aiken, Jr.
Director
Aeronautical Systems Division

Preface

More than 10 billion gallons of fuel are burned each year by U.S. commercial air transports. If only a 5 percent improvement in their operating efficiency could be achieved, the United States would save 500 million gallons annually. . . and a 50 percent gain is in the realm of possibility with improvements currently being researched in aerodynamics, propulsion, and aircraft construction.

The nation's air transportation system is a multibillion dollar industry, employing over one million Americans and accounting for more than six times as many passenger miles as its nearest commercial people-moving competitor, the intercity bus lines.

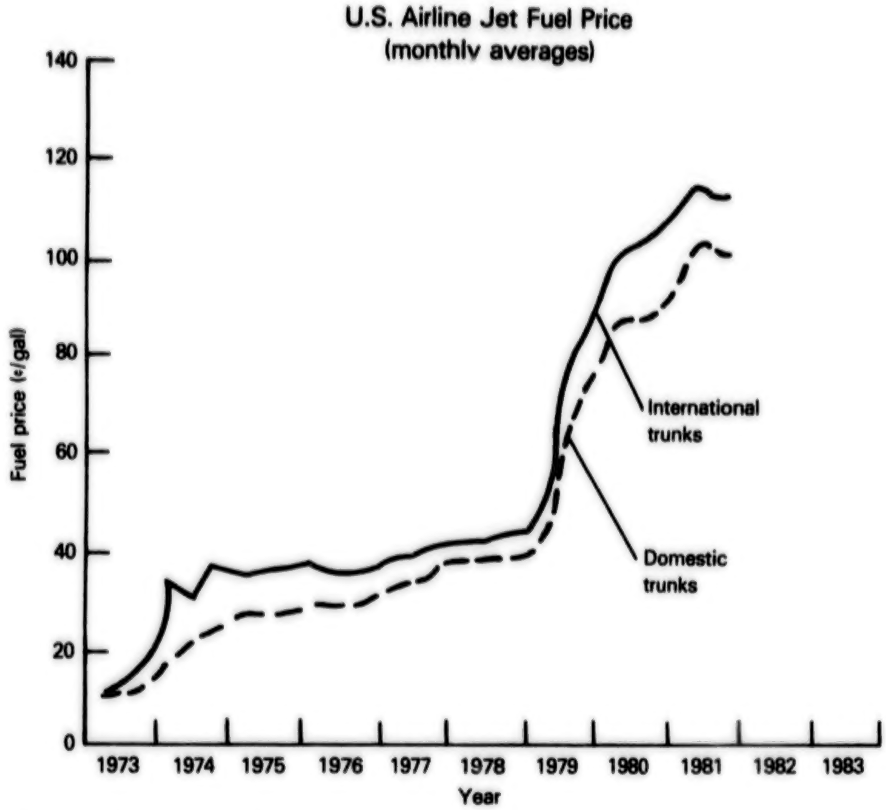
Most aircraft in the current worldwide airline fleets are expected to reach the end of their normal lifetimes in the 1980s, opening up a free world market for new aircraft projected to be greater than $200 billion before 1990.

American technology has dominated this international market for years; about four of every five civil air transports in the free world are made in the United States. Over the past decade, however, this lead has been challenged significantly by foreign competitors aided by government financial backing. In 1980 the aerospace industry still led all other categories, even agriculture, in net U.S. exports, but that lead was rapidly being eroded by foreign competition. One measure of what the loss of future air transport sales can mean is the estimate that a single jumbo jet sold abroad offsets the import of 9000 small foreign cars.

By the early 1970s it had become increasingly evident that the era of plentiful, inexpensive petroleum-based fuels was ending and that fuel cost was becoming a far more significant factor in air transport economics. From 1973 to 1975 the fuel prices paid by U.S. airlines almost tripled. In 1973 the price of airline fuel was 12 cents per gallon—by 1982 it had risen to $1.00 per gallon. Fuel costs rose from 20 percent of a typical airline's direct operating costs in the early 1970s to 60 percent by 1982.

Conservative projections indicate a fourfold increase in air transportation fuel consumption by the end of this century, accompanied by substantial cost increases. As a result, airlines are giving increased emphasis to fuel economy in buying new aircraft. If the United States is to reassert its lead in the transport market, it will have to build airplanes that give maximum seat miles per gallon.

The National Aeronautics and Space Administration (NASA) had generated projects that resulted in fuel efficiency, but it was not until January 1975, in the midst of the Arab oil embargo, that the U.S. Senate requested



Source: Civil Aeronautics Board

development of a program to provide the advanced technology needed for aircraft fuel conservation. From the outset, it was recognized that the value of the program would depend largely on how effectively and rapidly the resulting technology could be transferred to industry and incorporated into future designs. To this end, the aerospace industry was directly involved with NASA in both the development of the program plan and the conduct of major portions of the research.

In fiscal year 1976 the NASA Aircraft Energy Efficiency (ACEE) program was initiated to demonstrate a spectrum of propulsive, aerodynamic, electronic, and structural advances that could achieve the desired results. The technical changes spanned the range from near-term modest refinements in conventional technology to larger evolutionary technical gains for the mid to late 1980s and to major revolutionary innovations for the 1990s.

ACEE is composed of six advanced development projects aimed at cutting fuel consumption of future civil air transports and their military counterparts by significant margins:

Project	Potential Fuel Savings (%)
Engine Component Improvement	5
Advanced Energy Efficient Engine	10–15
Advanced Turboprops	20–40
Composite Structures	10–20
Aerodynamics and Active Controls (Energy Efficient Transport)	10–20
Laminar Flow Control	20–40

A key part of the ACEE program, and the most significant factor in all the technological developments, is that, although the potential benefits of individual technologies may appear small, the synergistic effects can be quite significant. For example, composite materials can provide structural improvements in the classic sense of reduced weight, cost, number of parts, etc., but they also may permit designers to use higher aspect ratios and forward-swept wings and perhaps provide the surface smoothness necessary for laminar flow. This synergism is a major thrust of ACEE.

With industry already utilizing developments from the ACEE program, it is hoped that the full potential of this budding technology can be tapped. Total NASA research expenditures for the 10-year program, beginning in 1976, are estimated at $670 million, including adjustments for inflation, for a potential savings of about 2 billion barrels (84 billion gallons) of fuel for the U.S. airlines from 1980 to 2005. At the 1982 price per gallon, that amounts to about $84 billion. The benefits can go far to help assure continued U.S. dominance of the world transport aircraft market and can provide major support toward a favorable balance of export-import trade.

Table of Contents

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Chapter 1
The Beginnings

From its establishment in 1915, the National Advisory Committee for Aeronautics (NACA) provided basic research results and advanced aeronautical technology of use to industry and the armed forces. When the National Aeronautics and Space Administration (NASA) came into being in 1958, NACA's functions were incorporated into the new organization, and a core of research in the aeronautical disciplines has been maintained.

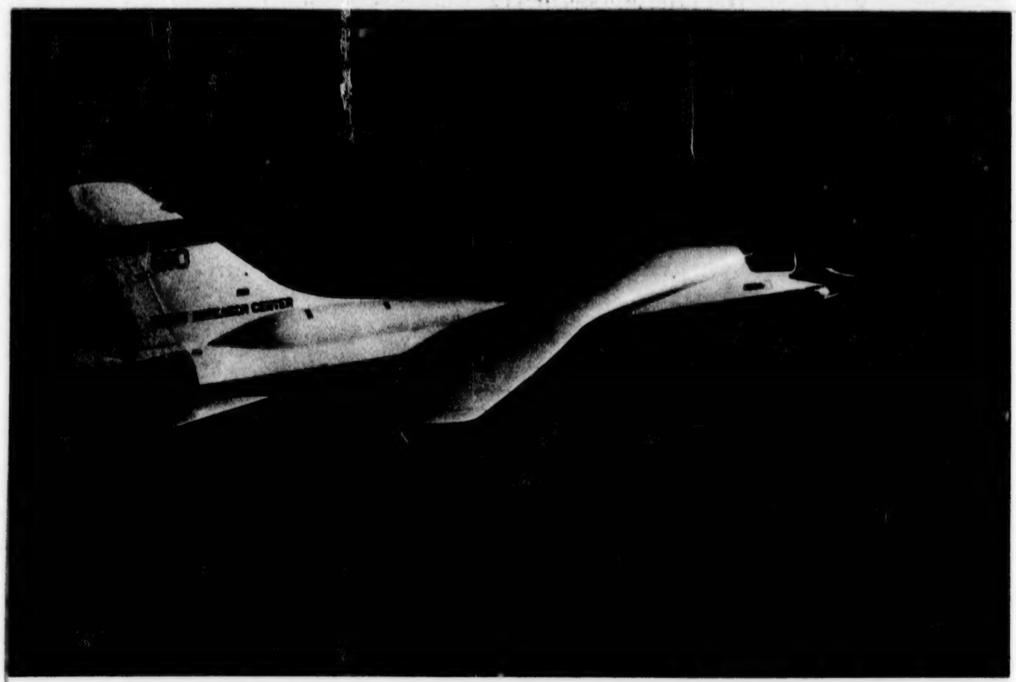
NASA has been unique in its ability to carry out national research and development programs by providing independent, objective technical consultative services for U.S. industry. It can reach far into the future to research and demonstrate technological feasibility that would be far too risky and expensive for a single company. The results of all NASA investigations, with the exception of classified military research, are offered through documents and seminars so that the technology may be used. This has far-reaching economic benefits not only for the companies that choose to develop the findings but also for the general well being of the population.

Until the 1970s, the trend in commercial transport aircraft normally centered around machines that would go higher, faster, and farther. The culmination of this long chain of events was the supersonic transport (SST), which was cancelled in March 1971.

CRUISE AERODYNAMICS

A large portion of the aeronautical research undertaken by NASA dealt with cruise aerodynamics, using unconventional airfoils and the area rule concept. The latter was used primarily on fighter aircraft to achieve greater speed, giving the distinctive "Coke bottle" shape prominence. A high-aspect-ratio swept wing with a high wing loading was then applied to transport aircraft, taking advantage of a quite different looking airfoil. The wing was long and narrow, appearing feather delicate. The sleek wing yielded a major improvement in cruise performance.

Application of this new airfoil, which became known as the supercritical wing, to practical hardware became part of NASA's Advanced Technology Transport (ATT) program, started in mid-1970 with a goal of saving time rather than fuel. The objective of ATT was a superior subsonic long-haul aircraft that could cruise just below the speed of sound, or Mach 1.



Long before NASA's ACEE program was officially under way, technology that boosted performance, and thus improved fuel economy, was being tested by the agency. One of the major breakthroughs was the NASA "supercritical wing," shown here being flight tested on an F-8 Crusader.

Absorbing the research that had gone into the previous Civil Aviation Research and Development (CARD) study of 1969, ATT soon became "the Apollo program of aeronautics" by incorporating several advanced concepts under one roof. Composite nonmetallic materials, recognized for their high strength-to-weight and stiffness-to-weight ratios since the late 1950s, were added. Active controls were incorporated from the NASA Active Controls Aircraft program, utilizing computers to move the control surfaces. Advanced propulsion technology was added as well.

United Airlines and American Airlines were contracted to evaluate the buying of aircraft with supercritical technology on the basis of higher productivity—hauling more people faster. Boeing, Lockheed, and General Dynamics designed aircraft with beautiful composite curves, large fairings and strakes, and none of the contemporary barrel shapes on current airliners. Because of the aerospace industry's depression at the time, the costs would have been too high for a company to produce an airplane an airline could afford—there were few inexpensive methods of construction for these exotic shapes. Since no one could afford a Mach .98 transport, NASA changed the program (and its name) to one that would reflect research into the aerodynamics of the future—Advanced Transport Technology—rather than one leading to a flying airframe.

Although the supercritical wing was originally designed to push the Mach number up to .9, this number was reduced to Mach .8 because of the fuel crisis, and the wing was made thicker for better structural efficiency and to carry more fuel. An I-beam structure was utilized to achieve a lighter wing, and the thicker

On an unusually humid day over the Mojave Desert in California, pilot Einar Enevoldson executes a tight, 4-G turn in the TACT F-111 equipped with a test supercritical wing. Wingtip vortices are clearly visible.

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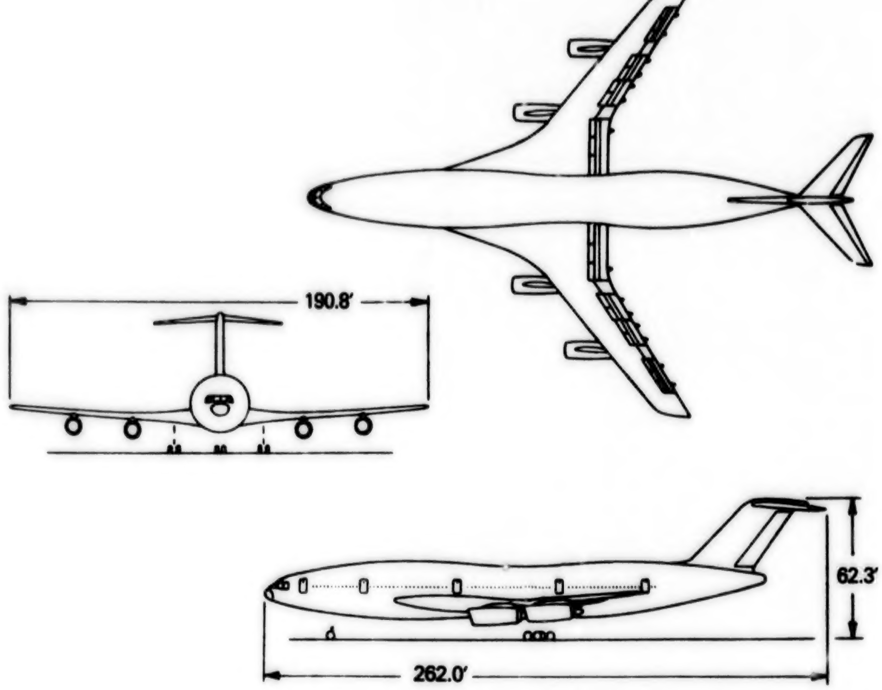

Lockheed's 400-passenger version of the Advanced Technology Transport designed to cruise at Mach 0.95. The area rule shape could have been a nightmare to manufacture.

section resulted in greater strength. As the wing was reduced in sweep from 35 to 30 degrees, the aspect ratio went from 10 to 12, compared to 7 for DC-10s and L-1011s at the time. With an aspect ratio of 10 and a 30-degree sweep, wing thickness ratios were 15 percent at the root, 13 percent at the engine pylon station, and 10 percent at the tip. In other words, as the wing span increased and the wing area decreased (leading to a rise in the aspect ratio number), efficiency increased.

From the ATT program came the concept of terminal area compatibility and the Terminal Configured Vehicle (TCV), a Boeing 737 operated within the airport terminal area environment to investigate ways to save time, energy, and operating costs and to evaluate new techniques and cockpit displays. Fuel saving was a small part of the program, but the performance gains converted easily into fuel economy.

FUEL CONSERVATION

As the fuel crisis began to be felt in 1973, the Energy Trends and Alternate Fuels (ETAF) program was initiated by NASA to seek better use of petroleum and to investigate other fuels such as hydrogen. For the first time, energy

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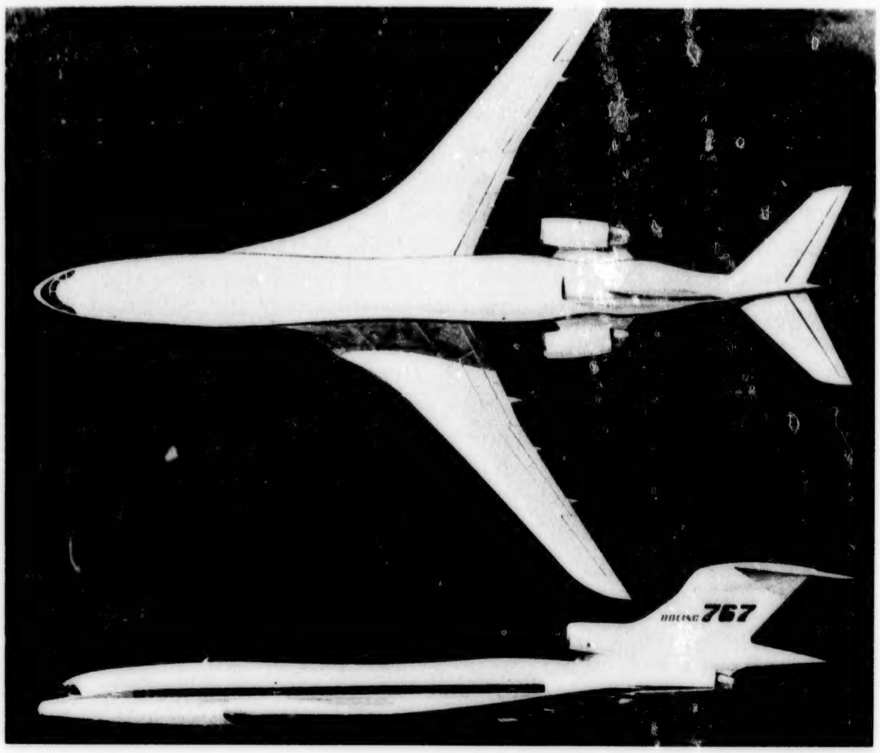


While the Advanced Technology Transport program was under way, Boeing was designing its 767 and 757 airliners. This was the initial 767 configuration using ATT requirements.

conservation was emphasized in light of what might happen if petroleum ran out. Coincidentally, the transport technology high performance gains translated very well into fuel economy; thus NASA had a head start on the problem, now centered around fuel savings rather than higher, faster, and farther.

Now other areas of research were incorporated. Laminar flow control had been investigated in the 1960s with the U.S. Air Force's X-21, which sucked boundary layer air through narrow spanwise slots in the wing—it was proven to work, but not without insurmountable maintenance and construction obstacles. The payoff of laminar flow was deemed high enough to reinstitute research.

Endplates or winglets were reinvestigated. These wingtip devices had been suggested in an 1897 patent, but the new twist was to carefully tailor a lifting surface on the end of a wing to reduce the induced drag. In supersonic studies, endplates had demonstrated an ability to increase cruise speed. When these small vertical fins were tested further, fuel efficiency increased as drag was alleviated.

In composite structures research, replacing metal with glass, graphite, boron, and epoxy slabs decreased aircraft structural weight by 25 percent while increasing strength for high cruise speeds...and saving fuel. Active controls

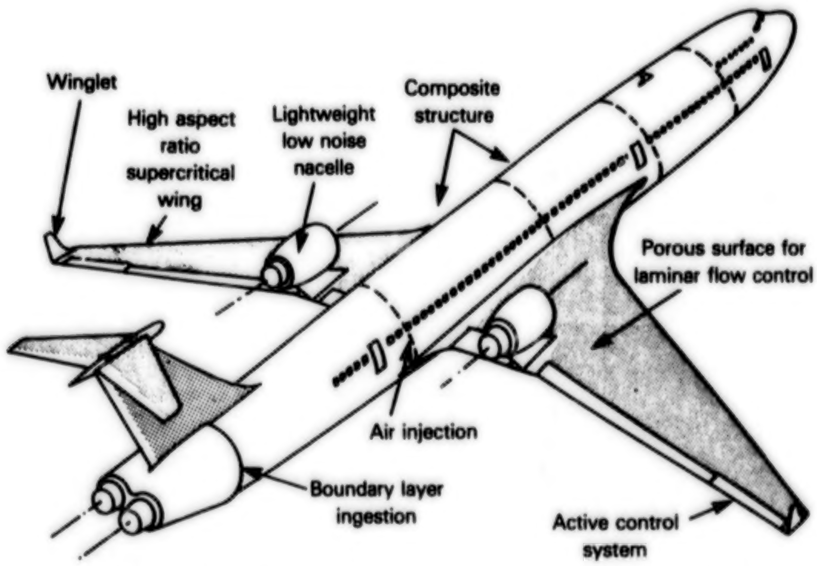
moved surfaces by digital fly-by-wire systems rather than hydraulics and torque tubes. As a result, the control surfaces were smaller and lighter, increasing both cruise efficiency and fuel economy.

By early 1973 propulsion studies were begun to investigate energy/transportation scenarios for NASA use. In early 1974 a program plan for energy-conservative aircraft propulsion technology was generated, recommending engine and engine cycle studies, component technology, demonstration of new technology on current engines, and an advanced turbofan demonstrator. Soon General Electric and Pratt & Whitney were under contract to study conventional turbofan engines designed for low fuel consumption and advanced unconventional concepts. An advanced acoustic composite nacelle was studied along with many other revolutionary features. The REFAN project, which had been initiated prior to the fuel crisis to reduce noise, increased efficiency in a line turbofan engine, with a resulting improvement in fuel consumption.

Hamilton Standard was asked to consider an advanced turboprop with an entirely new propeller that could handle Mach .8 speeds—the potential fuel efficiency was as high as that with laminar flow control and just as hard to research. The new shape was nicknamed the Propfan.

By the summer of 1974 American Airlines was evaluating for NASA the extent and causes of engine performance deterioration in its fleet, attempting to determine exactly what caused engines to consume increasing amounts of fuel.

By January 1975 it was considered imperative that energy efficiency be given top priority in NASA's aeronautical research effort, with the prime pur-



By the time advanced transport technology was defined, the fuel crisis had begun, and studies indicated that a fuel-conservative aircraft would have to incorporate some or all of the features identified in this 1974 drawing.

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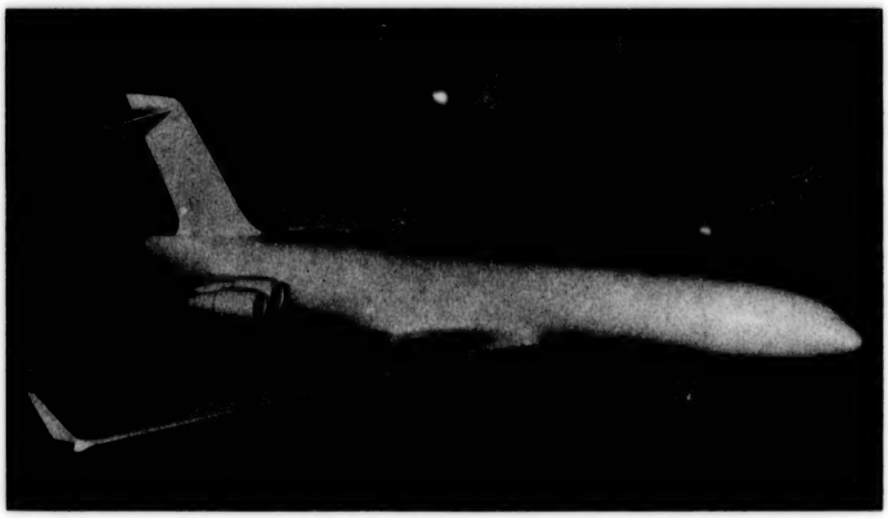
pose of reducing future aircraft fuel consumption and thereby insuring against unacceptable increases in the cost of air transportation.

Also in January 1975 NASA was requested by the Senate Committee on Aeronautical and Space Sciences under Senators Moss and Goldwater to develop a program reflecting these needs. The request referred to the current efforts aimed at achieving NASA's objective of preserving the role of the United States as a leader in aeronautics, specifically highlighting those projects which would enable U.S. industry to provide a new generation of fuel-efficient commercial aircraft. By this time, research had evolved from general aeronautical research and development to research into higher productivity, noise and emissions control, reduced delays in terminal areas, and fuel efficiency.

Industry has been reluctant to make the kind of intensified investment required for the ATT program. Thus, the Senate requested that NASA, in consultation with industry, work toward demonstrating the technology necessary to make possible a new generation of fuel-efficient aircraft by a stated date. Such aircraft were to have the same general operating characteristics as those currently flying, would meet safety and environmental requirements, would be similar in cost, could be flying in the 1980s, and would show a significant improvement in fuel efficiency.

The program was to be developed in such a fashion that technology transfer would be rapid, and the program plan would specify major milestones and fuel savings percentages, describing the planned efforts and costs.

Although many concepts, some very impractical, were available for study, the ATT and ETAF programs were ideally suited to be the basis of a new program. NASA assembled a task force to identify the technological advancement



1977 model of future fuel-efficient transport.

opportunities. Government scientists and engineers from NASA, the Department of Transportation, the Federal Aviation Administration, and the Department of Defense made up the team that worked with engine and airframe manufacturers, airlines, and several advisory boards and councils.

The task force produced a report outlining a technical plan for improving aircraft fuel efficiency, the estimated resources required, and the expected benefits. Six aeronautical technology elements were identified, involving propulsion, aerodynamics, and structures in which accelerated and expanded government research and development efforts, along with industry efforts, could improve fuel efficiency by up to 50 percent.

The plan was submitted to the Senate committee in special hearings conducted in September, October, and November 1975 and then endorsed. It was recommended that NASA implement the program in fiscal year 1976. With a boost from years of previous research, the new Aircraft Energy Efficiency (ACEE) program was off and running in a race with rising oil costs.

Chapter 2
Engine Component Improvement

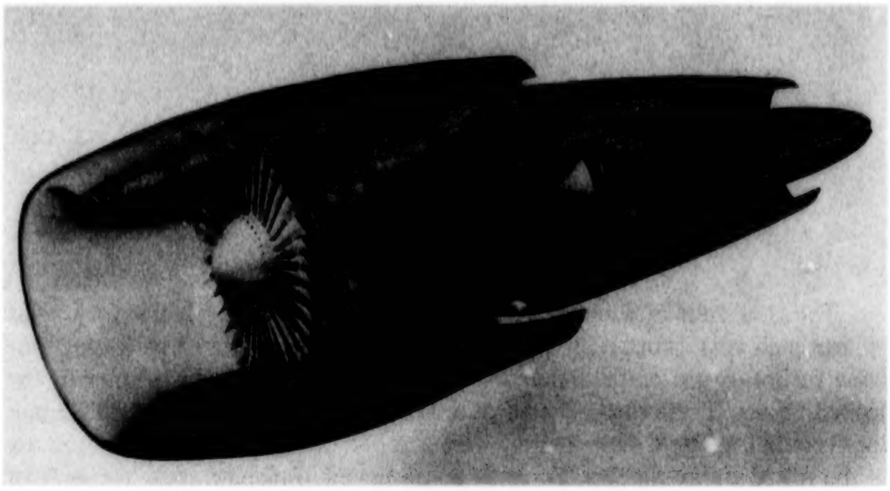
The U.S. fleet of commercial aircraft consumes about 10 billion gallons of jet fuel each year. Almost all of these jet transports are powered by one of four basic turbofan gas turbine engines, three of which are manufactured in the United States. These three, the Pratt & Whitney Aircraft JT8D and JT9D and the General Electric Company CF6, represent the vast majority of engines in use in the world today and are likely to be on the air transport scene for at least another two decades.

As an engine runs in everyday use, it is subjected to normal wear and tear. Sand, dust, or tiny stones picked up while the aircraft is on the ground cause nicks in the fan blades. The tips of the compressor blades wear down. The combustors sometimes warp under prolonged exposure to heating and cooling cycles. Seals that keep hot gases contained and directed develop leaks. The turbine blades, whirling at high speed in the high temperature of the combustors, erode in the gas flow.

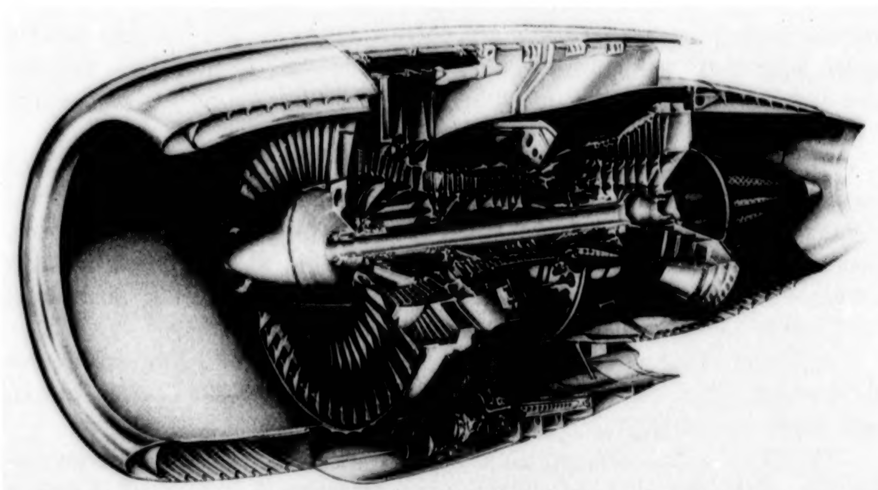
Although these engines regularly run 10 000 hours or more between major overhauls, the result is a gradual degradation of engine performance in the form of lower thrust or increased fuel consumption and higher operating temperatures. Overhauls restore only part of the lost performance; the engine reenters service with lower thrust or with higher fuel consumption for the same thrust level than it had when new.

As a part of the overall ACEE program, the NASA Lewis Research Center in Cleveland, Ohio, was assigned the responsibility of managing Engine Component Improvement (ECI).

The ECI project was expected to provide near-term results for the commercial fleet, with effort directed toward the development of components to reduce the fuel consumption of the three engines mentioned above by 5 percent and the identification of design criteria to minimize the performance deterioration of current and future engines. The program was divided into two parts: performance improvement and engine diagnostics. Performance improvement focused on the demonstration of technically and economically viable fuel-saving modifications for existing and new production JT8D, JT9D, and CF6 engines, with a target of introducing new engine components into the fleet by 1980 to 1982. The focus of engine diagnostics was the identification of the causes and magnitude of performance losses and the recommendation of methods to minimize performance deterioration in current (CF6 and JT9D) and future turbofan engines.



GE's CF6 high bypass turbofan, which powers the Douglas DC-10.



Pratt & Whitney's high bypass turbofan, the JT9D, which powers the Boeing 747.

By February 1977 the first contracts were awarded to Pratt & Whitney Aircraft and General Electric. The two prime contractors in turn placed subcontracts with Douglas Aircraft Company, Boeing Aircraft Company, American Airlines, Trans World Airlines, and United Airlines. NASA Lewis also had contracts with Eastern Airlines and Pan American World Airways to provide an independent assessment of the program objectives and results.

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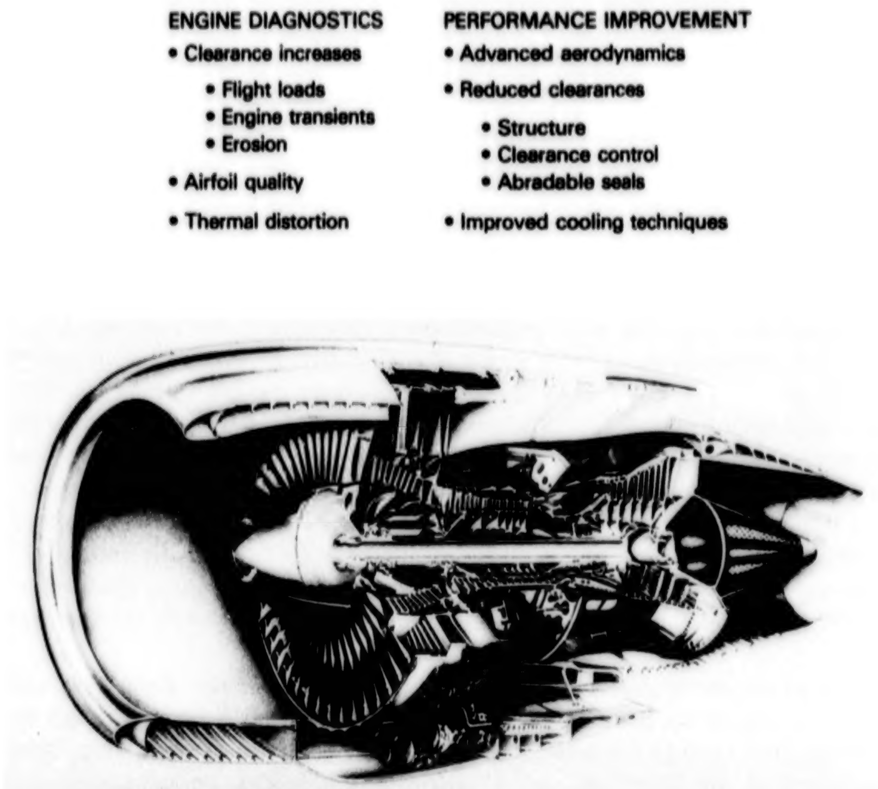
ENGINE COMPONENT IMPROVEMENT



PERFORMANCE IMPROVEMENT

During the initial performance improvement investigation, 58 General Electric and 95 Pratt & Whitney concepts were screened for fuel savings potential by a team of representatives from NASA, General Electric, Pratt & Whitney, Boeing, Douglas, United, American, TWA, Pan Am, and Eastern. Each concept was evaluated using a cost/benefit methodology to ensure that they would be technically sound and economically acceptable to the airlines. Sixteen concepts were selected as the most promising—seven for the CF6, four for the JT9D, three for the JT8D, and two aircraft-related concepts. They involved the following areas:

CF6 — fan, front mount, high-pressure turbine aerodynamics, high-pressure turbine roundness control, high-pressure turbine active clearance control, and short core exhaust nozzle.

JT9D — high-pressure turbine active clearance control, high-pressure turbine vane thermal barrier coating, high-pressure turbine ceramic outer air seal, and fan technology.

JT8D — high-pressure turbine outer air seal technology, high-pressure turbine blade, and trenched tip high-pressure compressor.

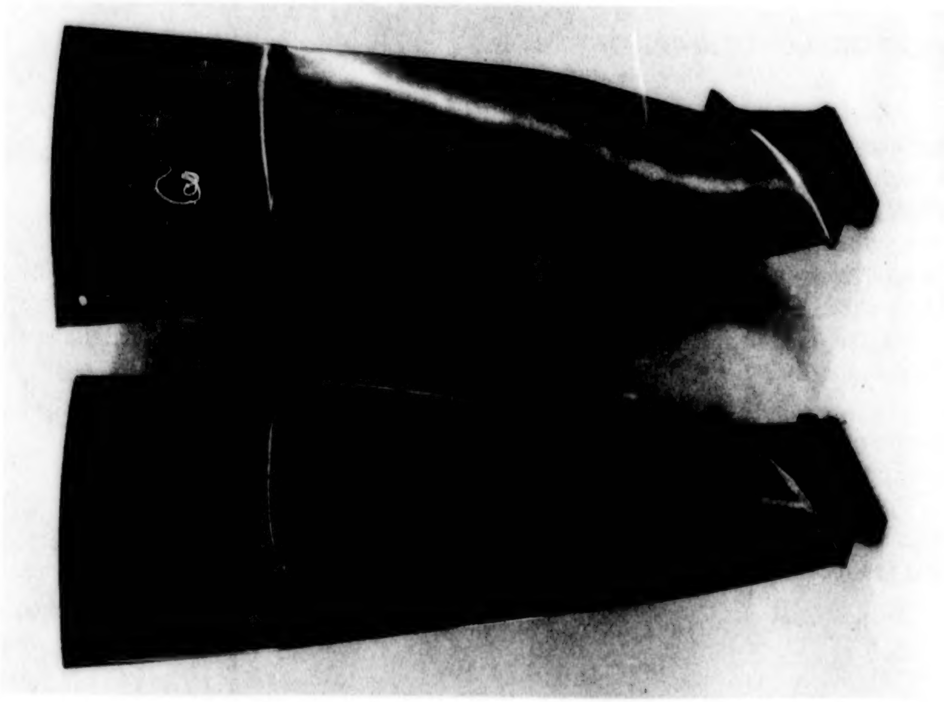
Aircraft-related — compressor bleed reduction for DC-10 and nacelle drag reduction for DC-9.

At the time of the study, fuel prices of 45 cents per gallon were typical; since then, prices have more than doubled, making near-term results much more valuable. An important factor for airline acceptability is the payback period projected for each concept, that is, actual cash outlay divided by annual cash savings. No matter how good a concept may appear, if it does not save money for the airlines, it is a dead issue. With spiraling fuel costs, payback periods have shortened, making these early performance improvements more attractive.

The central factor in every aspect of engine development, and of the entire ACEE project, is to drive down specific fuel consumption (SFC). SFC is a measure of engine efficiency, defined as fuel flow rate (pounds per hour) divided by engine thrust (pounds of force). The lower the ratio, that is, the lower the fuel flow rate for a given thrust, the more efficient the engine.

The amount of fuel burned by an aircraft is a function of several factors, primarily engine SFC and aircraft lift-to-drag ratio, which determines the aerodynamic efficiency of the airframe. A gain of just one-tenth of one percent in SFC is considered by the airlines to be a major improvement over the long term.

A jet engine behaves somewhat like a pump; it takes in air at the front and pumps it toward the back, adding energy to it and moving it faster through the exhaust than through the inlet. The extra energy comes, understandably, from



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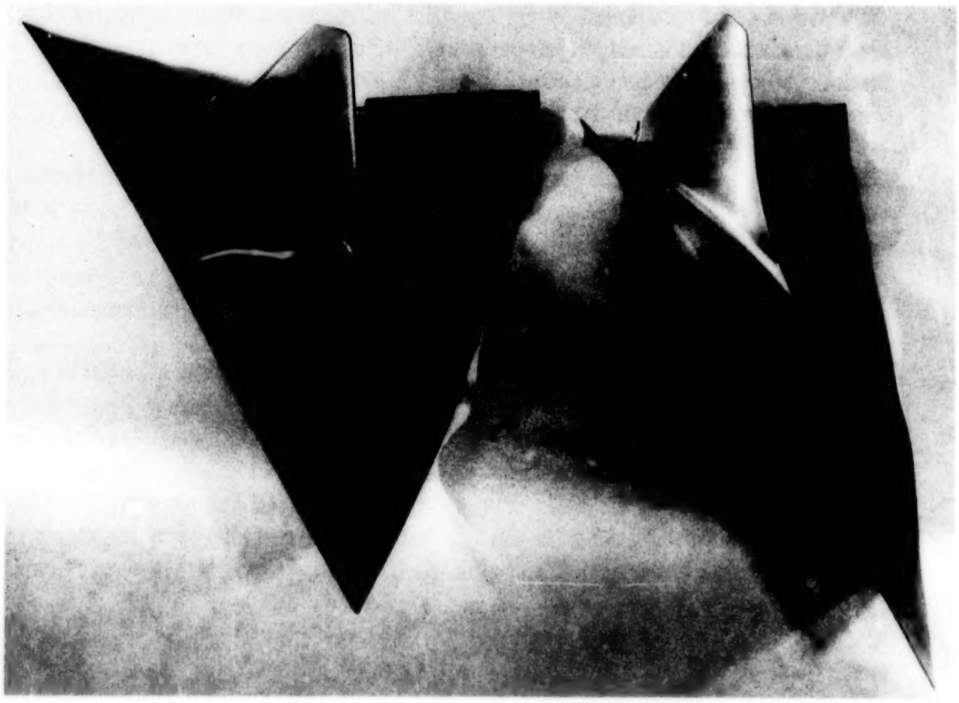
burning fuel in the air. A pump that leaks is obviously inefficient; a jet engine that leaks its high-pressure air is also inefficient. One major task of the designers of improved components was leak reduction.

Leaks exist in seals that are intended to keep high-pressure gases from escaping the main flow path; they exist between the tips of the rotating fan, compressor and turbine blades, and the engine case, allowing air to leak past without being properly handled by the rotating part. Leaks at the roots of the rotating blades allow leakage into the engine housing. Consequently, both tip clearances and seals received major attention in the ECI program.

Improved aerodynamic design of the compressor and turbine can increase engine efficiency. By using new blade materials or ceramic coatings, erosion and corrosion of the blades can be reduced. A better cooling system for the turbine and ceramic-coated blades and vanes can reduce the amount of air needed to cool the hot turbine section and further improve efficiency.

General Electric developed an improved fan package for the CF6 engine, which powers the Douglas DC-10, Boeing 747, and Airbus-Industrie A300, that featured revised fan blade aerodynamic design and reduced fan tip clearances due to a fan case stiffener. The improved fan has the single part-span shroud moved rearward on the blade, and the blade camber (arched surface) was modified. The original and improved fan blades are completely interchangeable in sets, both being common to the CF6-6 and CF6-50. The fan case stiffener

Two views of the original (left) and improved fan blades and shrouds on the CF6 engine. The fan shrouds were moved aft on the blade for improved aerodynamic efficiency.



reduces structural deflections, permitting a smaller fan blade tip clearance and increased efficiency.

The results of the fan package development indicated a significant performance advance. Compared to the original fan, the improved version had increased fan airflow for a given speed and increased aerodynamic efficiency that resulted in an SFC reduction of 1.8 percent in both CF6 models. Takeoff and climb noise levels remained the same.

A redesigned front mount on the CF6 effectively reduced the point loading in the compressor casing by applying load reactions to two points 30 degrees from the top vertical centerline. Engine thrust and vertical and side forces are transmitted through a series of links connected tangentially to the compressor casing forward flange. Localized distortion of the casing was reduced, decreasing the compressor blade tip clearances.

Mechanically, the modification worked quite well in reducing compressor blade tip clearance, since the compressor case local distortion was reduced by 29 percent for takeoff rotation and 42 percent for maximum static thrust. Simply stated, the rounder the engine, the less the blades will tend to rub on the circumferential walls of the case. This decreased clearance in the compressor produced a 0.1 percent cruise SFC reduction and, more important, a substantial and much desired increase in compressor stall margin.

The main features of the improved CF6-6 high-pressure turbine are single shank turbine blades, reduced turbine exit swirl that lowers the turbine midframe pressure losses, improved cooling flow requirements, increased solidity, smoother blade surface finish, and shroud mechanical and cooling improvements that reduce tip clearances. Engine test results demonstrated the thermal effectiveness and mechanical integrity of the redesigned turbine with better blade leading and trailing edge temperatures. The turbine's first-stage average temperature decreased significantly, with a 6 percent reduction in cooling flow, whereas the second-stage average temperature stayed about the same, with a 50 percent reduction in cooling flow.

Back-to-back engine tests (consecutive tests of an engine with and without the performance improvement concept) indicated a 1.3 percent cruise SFC reduction and a 10°C lowering of exhaust gas temperature. Because of the better performance retention characteristics, additional reductions of 0.3 percent in cruise SFC and 6°C in exhaust gas temperature are projected for long-service engines.

A short core exhaust nozzle system was developed for the CF6-50 engine that involved replacing the current core reverser/exhaust nozzle system with a reduced length fixed nozzle. Elimination of the core exhaust reverser also permitted a reduction in the engine core cowl diameter. The total weight saving was 325 pounds, with the additional benefits of reduced fan pressure loss and aerodynamic scrubbing drag. In back-to-back engine tests between the long and short core nozzles, a cruise SFC reduction of about 0.9 percent was obtained.

Improved mechanical design for high-pressure turbine roundness control (passive clearance control) on the CF6-50 included mass distribution of the supporting structure, shielding the supporting structure from cavity air recirculation (isolation from the hot gases that cause temperature differentials), solid shrouds, and modifications to the turbine midframe and struts. General Electric found that thermal rather than flight loads were the primary cause of distortion in its engines, so these modifications provided better rotor-to-stator thermal matching and improved turbine stator roundness. Cruise SFC was found to be reduced by 0.22 percent in new engines and 0.5 percent in older engines with high operational hours.

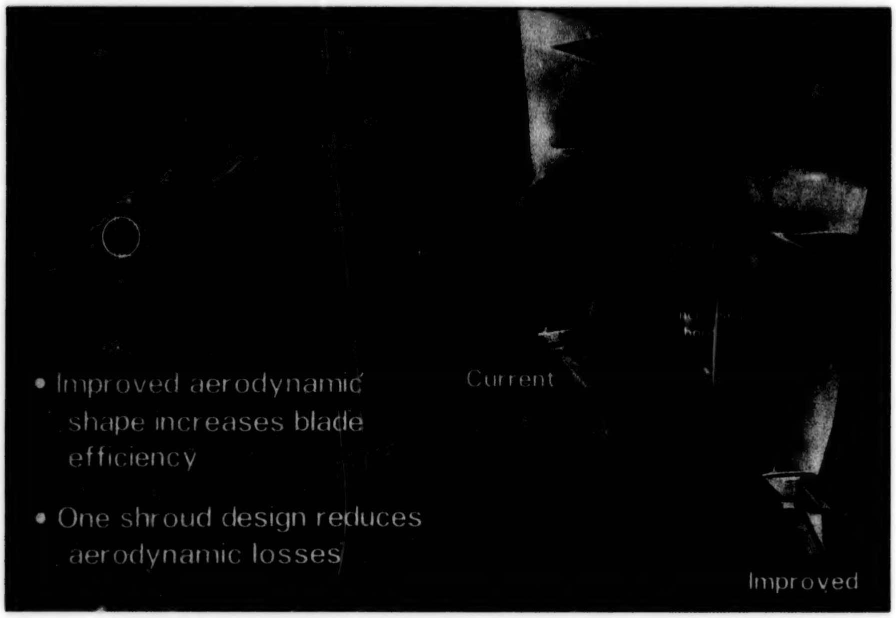
High-pressure turbine active clearance control was developed for the CF6-6 engine. Cooling air from the aft fan duct and the last compressor stage was piped to manifolds circling the turbine and then directed to impinge at appropriate shroud support flanges. The compressor discharge air was used to heat the turbine case during takeoff to avoid deterioration of clearances (rubs), and the fan air was used during cruise to reduce clearances, thereby improving efficiency. Cruise SFC was lowered by 0.7 percent, with a potential of 0.9 percent. The extensive structural changes required to implement the concept make its incorporation into new engine designs more attractive than modifying existing engines. This situation could change, depending on further developments in the fuel price structure.

The low pressure turbine active clearance control system used fan air continuously to cool the shroud supports, augmented with additional fan air during cruise to provide a reduction in blade tip clearance. The supplementary airflow was controlled by an on/off valve actuated by barometric pressure. An override actuated by the engine power level was provided to allow for increased clearances (less airflow) at flight idle in preparation for landing and reverse thrust operation. A cruise SFC reduction of 0.3 percent was achieved, with a potential of 0.45 percent with an improved piping and impingement system.

Pratt & Whitney was equally energetic in performance improvement in the ECI program. The JT8D and JT9D engines power the Douglas DC-9 and DC-10, the Boeing 727, 737, and 747, and the Lockheed L-1011 airliners.

For the JT9D engine, Pratt & Whitney worked on improving fan technology by eliminating one of the two part-span shrouds, creating better blade aerodynamics (multiple circular arc airfoils), and increasing the blade chord (width), which reduced the aspect ratio and the number of blades. The lower aspect ratio blade improves overall performance and has better flutter and foreign object damage characteristics. The reduced number of blades allows for a reduced number of fan exit guide vanes due to acoustic considerations, which also increases overall performance.

Fan efficiency improved to the point that an SFC gain of 1.3 percent was obtained at 90 percent of cruise thrust. Distortion tolerances, stress levels, and noise levels equaled or exceeded those for the current fan. Even though the re-



Improvements on the fan of the JT9D engine.

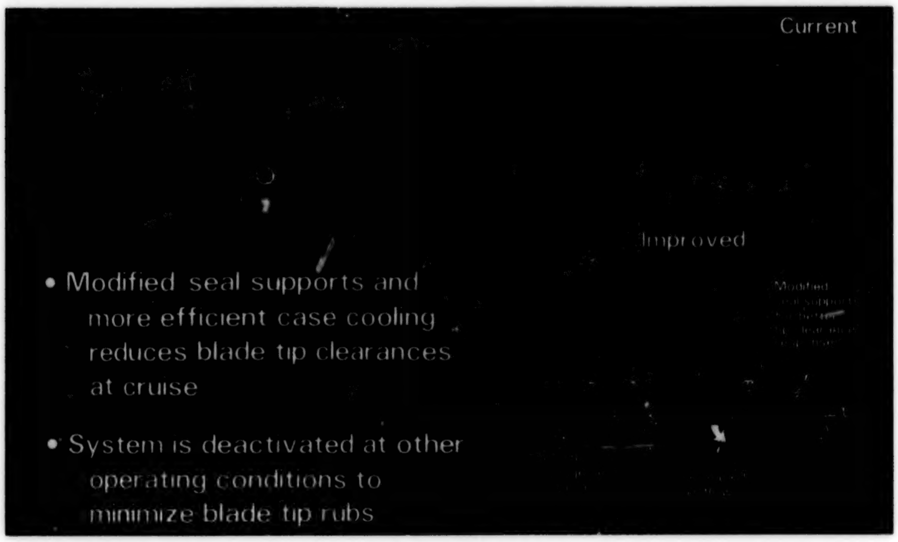
quirement of a somewhat different fan on the JT9D-7R4 for the Boeing 767 halted further development of this design, the test data base is being used in continuing JT9D fan improvement programs.

JT9D-70/59 high-pressure turbine active clearance control was achieved by encircling the turbine with perforated pipes that spray fan air on the turbine case during cruise, shrinking the case and seals. This shrinkage tightens the tip clearances and improves turbine efficiency. The air supply is off during takeoff, climb, and landing, when the engine is subjected to the most severe thermal structural loads. Since the case is hotter (without cooling air), thermal expansion of the case and seal supports provides larger clearances between the blade tips and the seals. The improved system incorporates an increased coolant air supply and a better distribution system, which results in a greater reduction in outer air seal diameter during cruise.

Simulated altitude engine testing of the system demonstrated an average cruise SFC gain of 1.4 percent when activated under cruise operating conditions, compared with a 0.7 percent reduction with the earlier system.

The ceramic thermal barrier coating on the JT9D high-pressure turbine first-stage vane platform permitted a reduction of cooling airflow. In addition, the film cooling holes on the vane platforms were eliminated to increase engine efficiency and lower fabrication costs. The insulating effect of the zirconia ceramic coating resulted in a 0.2 percent lowering of cruise SFC.

A high-pressure turbine ceramic outer air seal was also applied to the JT9D in combination with an abrasive blade tip embedded with silicon carbide "grits"



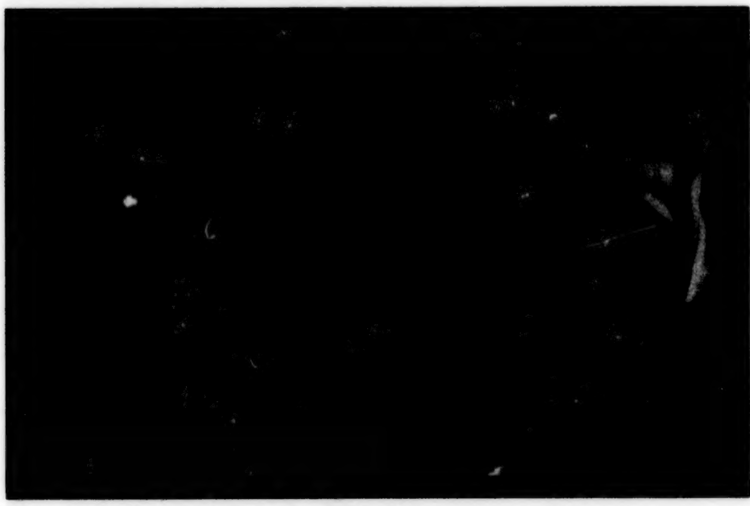
Improved active clearance control in the JT9D engine.

to provide a considerable improvement in abradability relative to current shroud/blade material combinations. This permits the use of tighter running clearances, and the ceramic shroud material acts as an insulator, reducing cooling air requirements. A cruise SFC improvement of 0.4 percent resulted.

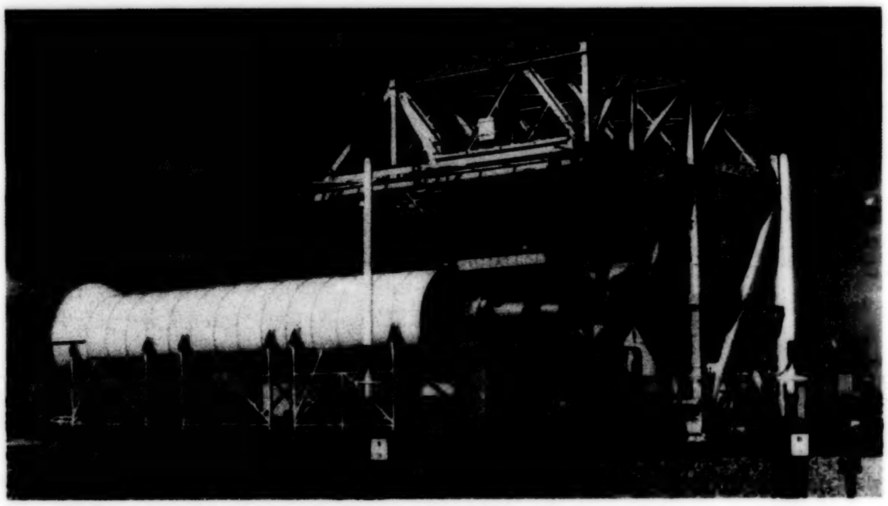
A new turbine blade on the JT8D featuring root discharge of the blade cooling air and a redesigned outer air seal improved the high-pressure turbine. The current JT8D high-pressure turbine blade uses a single-pass tip discharge cooling scheme. The improved blade uses a two-pass root discharge system. In the redesign, most of the cooling air discharge was relocated on the suction side of the blade. An average SFC reduction of 0.6 percent and a takeoff exhaust gas temperature of 6°C resulted solely from the improved cooling scheme.

In an effort to reduce air seal leakage past the turbine's tip shrouds, the first-stage outer air seal and blade cooling scheme were redesigned. Discharge of all the cooling air at the tip had necessitated a large blade tip clearance, with subsequent high leakage. Root discharge allows for the addition of another knife-edge seal at the blade tip and the extension of the honeycomb seal material to the trailing edge of the existing spoiler, thus reducing seal leakage. The redesign required a new casting, updated materials, and improved airfoil shape with reduced trailing edge thickness. The new airfoil has lower contour losses and better cooling effectiveness. The end result of these combined improvements is a cruise SFC reduction of 1.8 percent and an 18°C lowering in takeoff and exhaust gas temperature.

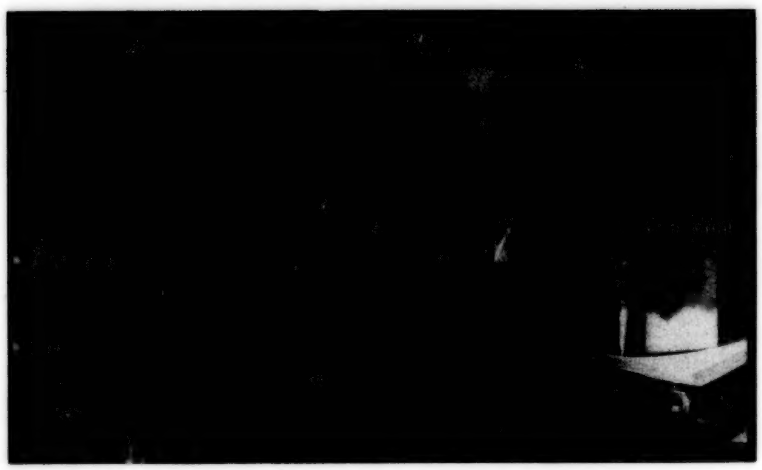
Abradable rub strips in the high-pressure compressor outer case also were incorporated in the JT8D to permit the compressor blade tips to run in a shallow trench. This allowed the blade tips to run line-on-line with the outer flow path of



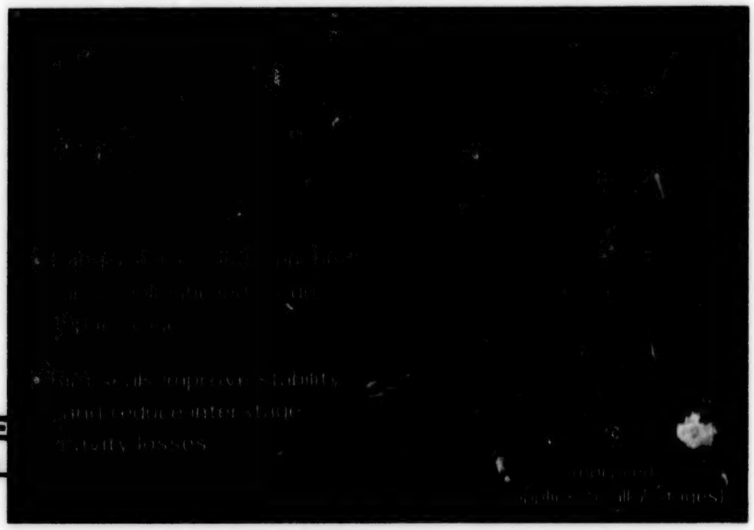
Thermal barrier coating in the JT9D high pressure turbine.



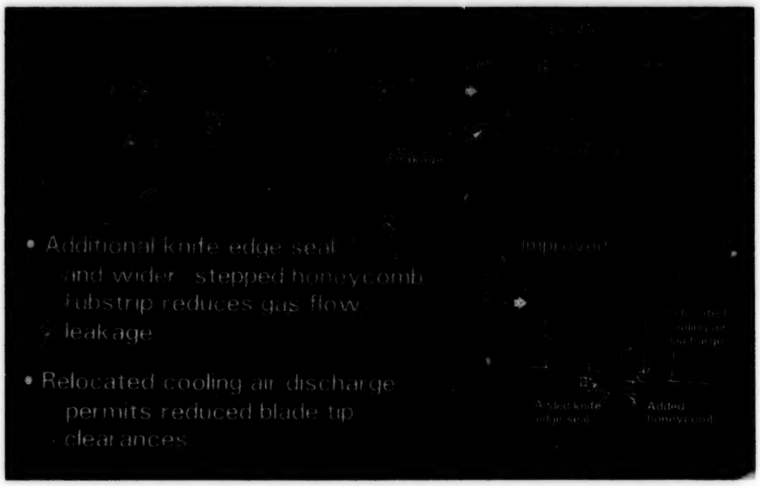
The JT9D mounted in the test facility for the 1000-cycle pacer endurance test in the thermal barrier coating program.



High-pressure turbine ceramic outer air seal on the JT9D engine.



Improvements in the JT8D high-pressure compressor.

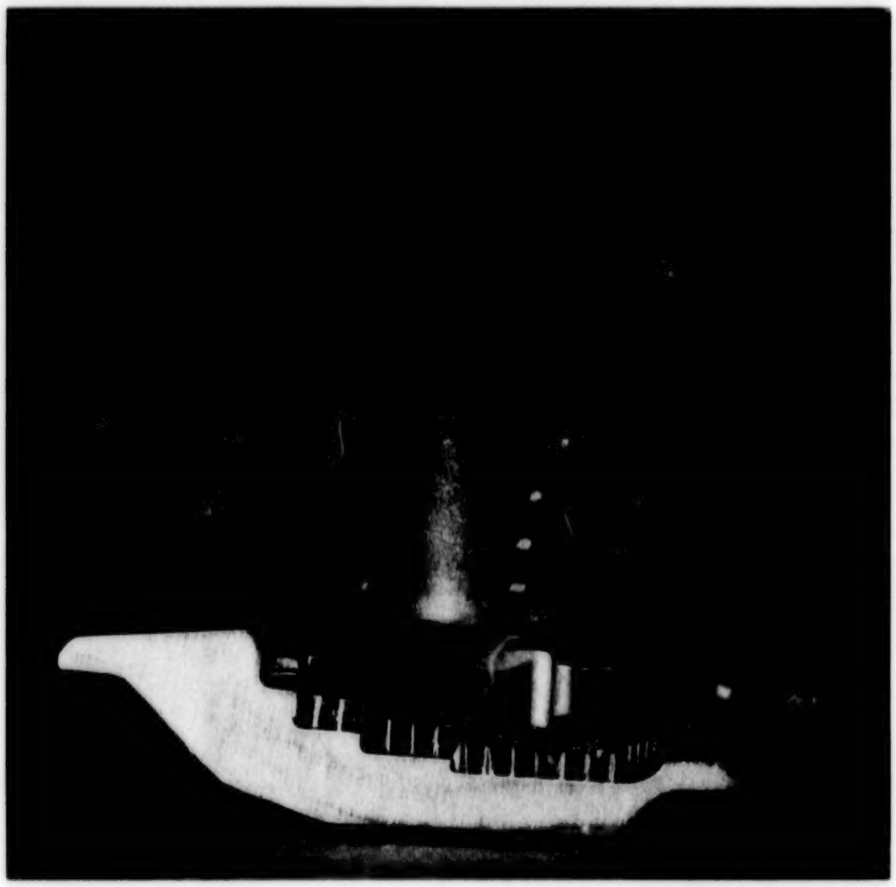


The JT8D revised high-pressure turbine outer air seal.

the compressor case at cruise conditions with tighter blade tip clearances. Rim seals were added along the inner flow path to reduce interstage cavity recirculation, thereby improving stall margin. The increased compressor efficiency amounted to a 0.7 percent reduction in cruise SFC.

The cabin air recirculation system developed for the Douglas DC-10 reduced compressor bleed air usage when added to the existing air conditioning systems. Fuel flow measurements in flight showed an SFC reduction of 0.8 percent for 50 percent less compressor bleed airflow. Airline reaction was quite favorable, since cabin comfort was improved through reduced ozone and increased humidity.

The current DC-9 thrust reverser is only partially faired over (covered), exposing a significant aerodynamic drag area. Modifications were made to the



Closeup of the JT8D revised high-pressure turbine outer air seal (above) clearly shows the changes when compared to the older system (right).

stang (housing over the reverser) by replacing it with a more complete fairing made of Kevlar/PMR-15 composite material. Not only did the new fairing have improved fatigue strength over the old aluminum design, but the cruise drag reduction achieved accounted for a 1.2 percent reduction in SFC.

The importance of these engine component performance improvement gains is their near-term application. By 1982 most of the improved components were flying and saving fuel, giving the companies involved a firm leg up in the commercial aircraft marketplace, where they are being challenged by foreign competition. Market projections indicate that if all 16 concepts are successfully introduced into service, more than 7 billion gallons of fuel may be saved through the expected lives of the engines.

ENGINE DIAGNOSTICS

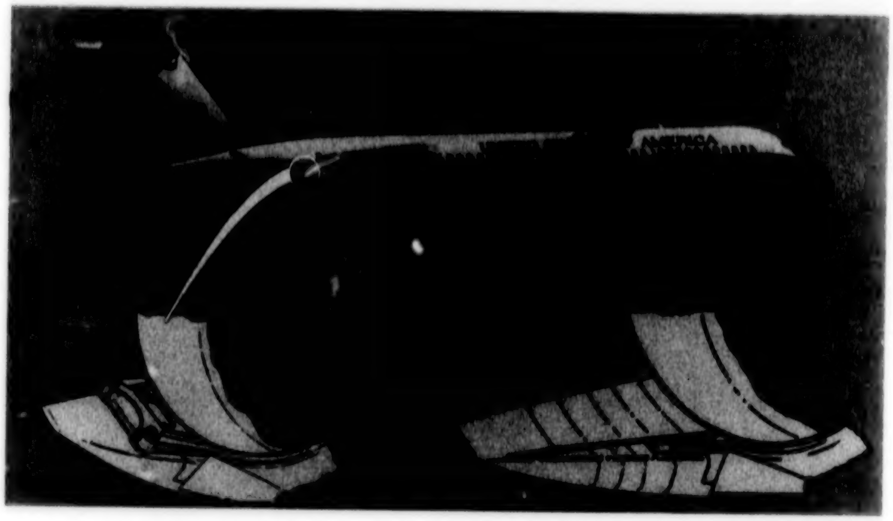
As stated before, the everyday use of an engine erodes its efficiency. Tiny objects picked up while the aircraft is on the ground nick the fan blades. Com-

pressor blade tips wear away. Combustors sometimes warp, and seals develop leaks. The result is a gradual degradation of engine performance in the form of lower thrust or increased fuel consumption and higher operating temperatures. Overhauls can restore only a part of the lost engine performance.

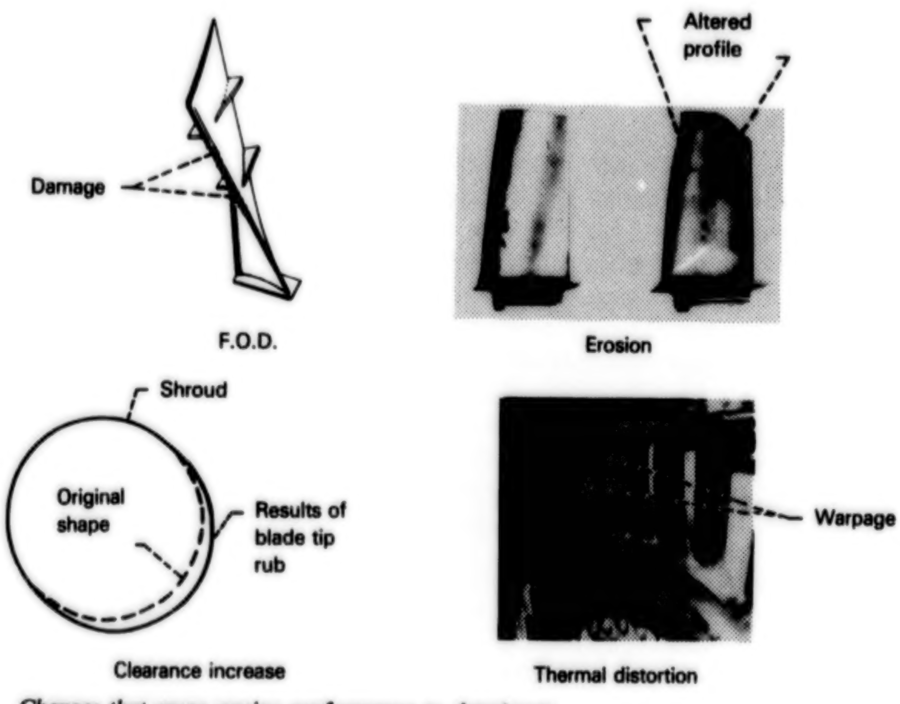
The goal of the engine diagnostics portion of the engine component improvement work was to determine the specific causes of performance deterioration by conducting ground tests and evaluating in-flight data for both new and used General Electric CF6 and Pratt & Whitney JT9D engines, which power the Douglas DC-10 and Boeing 747. Once those factors were determined, design information could be derived to improve both existing and new engines by making them less subject to performance degradation.

The general approach to the diagnostic studies took the following form:

1. Gathering historical (existing) data from engine tests at both airline and engine overhaul shops and from airline in-flight recordings and conducting inspections of used parts.
2. Evaluating the effects of deteriorated components and subsequent refurbishment on module and overall engine performance.



DC-9 thrust reverser stang changes.



Changes that cause engine performance to deteriorate.

3. Establishing statistical trends and analytical models of engine performance deterioration.
4. Isolating engine performance deterioration to specific events and/or modules and conducting special effects testing to quantify the mechanisms and magnitudes of engine performance deterioration.

Historical data were gathered from airlines representing about one-third of the free world's fleet of aircraft, aircraft companies, overhaul/repair organizations, and engine manufacturers. Included were data from engine testing, normal flight data and observations, and documented records of used parts condition and replacement rates.

In the cold section of the engine (fan and compressor), airfoil quality (foreign object damage, erosion, and surface roughness) was found to be significant. In the hot section, thermal distortion was one of the major factors causing among other things, warpage or distortion of vanes. Clearance increases resulting in efficiency losses occurred throughout the entire engine as a result of blades rubbing their outer shrouds.

An examination of the historical data revealed, for both engines, an early deterioration within the first few flights of an airplane. The average short-term performance loss for both the CF6 and JT9D engines ranged from 0.7 to 0.9 percent cruise SFC. Hardware/used part examinations showed that clearance increases were the predominant cause of short-term deterioration during the first flight and were a result of rubs between blades and stationary seals. The rubs in the JT9D were associated with deflections within the engine produced by aircraft-induced flight loads that occur at high angles of attack and fan airflow rate. Engine power transients to high power levels were also suspected of producing increases in blade tip clearances.

The CF6-6 data revealed that increased tip clearances in the high-pressure turbine contribute over 90 percent of the total short-term performance deterioration, associated with "hot rotor reburst." This produces rotor/case interferences that result in increased blade tip clearances due to different thermal growth rates between rotating and stationary structures. Although this is not normal, it occurs during aircraft acceptance tests or in avoidance maneuvers.

In general, the long-term performance deterioration for both the General Electric and Pratt & Whitney engines was on the order of 2.5 to 3.0 percent. It should be pointed out, however, that the engines would have undergone one refurbishment (overhaul) to restore a portion of the performance deterioration shortly after 1650 flights for the CF6 and 1000 flights for the JT9D. It should also be remembered that these long-term performance losses are cumulative values and include the short-term performance losses.

A closer examination of the data from both engines revealed that the causes of long-term performance loss were additional blade tip clearance increases in all engine modules, along with fan and compressor airfoil erosion/roughness. High- and low-pressure turbine thermal distortion was also a contributing factor.

It was found that, for the JT9D, a potential of about 0.7 percent cruise SFC was obtained with the normal high-pressure turbine refurbishment; for the CG6 the value was about 0.9 percent. In practice, however, not all performance deterioration is restored—about 0.1 percent SFC loss remains after each repair. Additional refurbishment activity could further reduce this value of unrestored performance.

Pratt & Whitney also acquired pre- and postrepair performance data as well as parts condition information from 32 JT9D-7A engines in Pan American World Airways' fleet of Boeing 747 SP Aircraft. Analysis of these data corroborated the historical data results, which indicated that the JT9D has a cruise SFC loss of about 0.7 percent during its early flight cycles and 2 percent in the long term. Clearance increases throughout the engine accounted for almost all the short-term increases and about half the long-term increases; the remainder was caused by thermal distortion in the turbines and increased airfoil and seal erosion in the fan and low-pressure compressor.

General Electric collected short-term data on the CF6-6 through test and inspections with an engine that was removed from a DC-10-10 prior to delivery to an airline. Tests following removal of the engine indicated a 0.9 percent cruise SFC increase over the level measured during engine production acceptance tests at General Electric. Again, backing up the historical data, the loss was primarily a result of blade tip-to-shroud rubs causing increased clearance in the high-pressure turbine module.

As a part of the long-term deterioration investigation for the CF6-6, two service engines were selected for conducting special tests. The results revealed the primary causes to be increased blade tip clearances, increased airfoil surface roughness and erosion, and parts distortion. Additional special testing was conducted to determine the contribution of individual modules and components to the overall increase in engine SFC. Separate tests of two fans, in which the fan blades were cleaned and the leading edges recontoured, produced a 0.4 percent average reduction in cruise SFC. Six low-pressure turbine modules were tested back-to-back with new and refurbished modules, and the average change in cruise SFC through low-pressure turbine deterioration was found to be 0.4 percent. The primary cause was clearance increases resulting from blade tip-to-shroud rubbing.

In both the short and long term, the JT9D and CF6 lost performance through increased blade tip clearances throughout the engine; therefore, investigations were initiated to better understand the cause and effect.

A major cause of increased clearances in the JT9D was believed to be flight loads (aerodynamic and inertial). An integrated NASA Structural Analysis (NASTRAN) model of the JT9D/747 installation developed jointly by Boeing and Pratt & Whitney was used to predict engine structural deflections, and fuel consumption increases were calculated at flight conditions of a typical acceptance flight test profile. When the structural deflections of the engine rotors and cases produced rubs between blade tips and outer seals, performance losses oc-

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cured in the form of increased operating clearances. These losses for each stage of each module were then determined through the use of influence coefficients relating increased blade tip clearances to increases in specific fuel consumption.

The results of this analysis indicated that nacelle aerodynamic (pressure) loads accounted for 87 percent of the total short-term engine performance deterioration (0.7 percent cruise SFC increase). Inertia loads, which primarily affect the high-pressure turbine and fan, caused about 13 percent of the deterioration. Simulated aerodynamic loads tests were then conducted with a specially prepared JT9D engine instrumented to measure performance, clearances, and case thermal gradients in a high-energy X-ray facility at Pratt & Whitney. The facility was modified with a specially designed loading device that used "belly bands" around the engine nacelle, connected to cables that were used to apply simulated flight loads.

X-ray and laser proximity probes measured blade tip and seal clearances. X-rays, both top and bottom, were taken at seven axial positions along the engine, and laser proximity probes were available for nine stages. In addition, 400 thermocouples and pressure taps were installed to measure engine case, flange and cavity air temperature, and pressure gradients.

The JT90 engine installed in an X-ray facility for load tests. Cables attached to the nacelle from above, below and at left tug on the engine to stimulate flight load conditions.

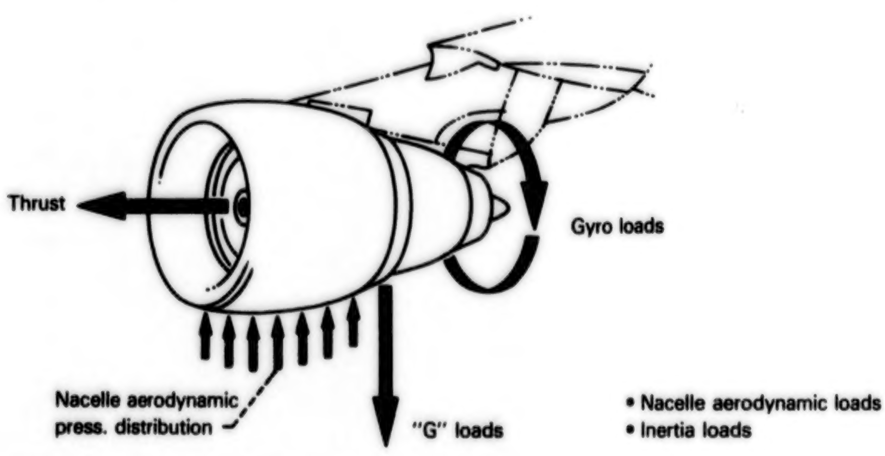
The tests were performed in three sequences: (1) determination of changes in engine running clearances due to thermal and thrust loads; (2) changes in engine static (cold) clearances established as a function of simulated inlet aerodynamic loads; and (3) operation of the engine at power while applying simulated inlet aerodynamic loads to determine the combined effect of thrust, thermal, and inlet loads on clearances. Results revealed an increase in cruise SFC of 0.8 percent.

The final step in the flight loads program was dramatic and highly successful. Boeing provided the no. 1 747 for use in flight tests with instrumented JT9D engines. Under the Nacelle Aerodynamics and Inertia Loads (NAIL) program, Lewis Research Center worked with Pratt & Whitney to gather engine data, and NASA's Langely Research Center in Hampton, Va., teamed with Boeing to gather aerodynamic data.

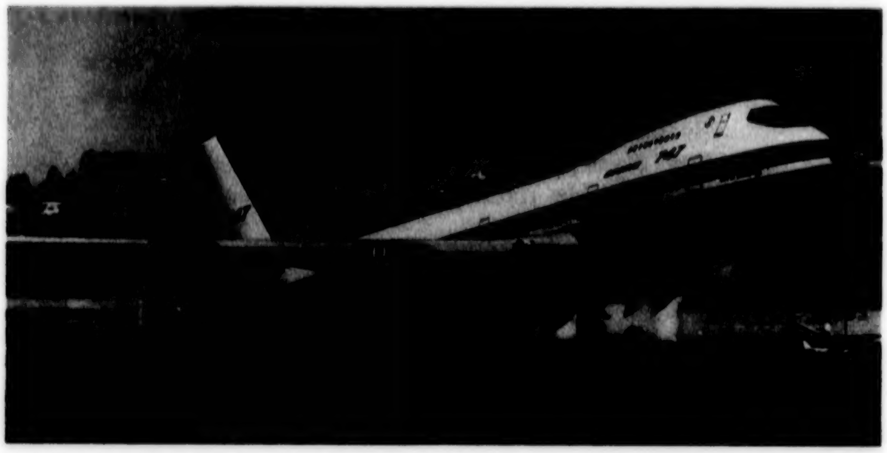
In instrumenting the right inboard and outboard engines, 693 pressure measurement points, 30 accelerometers, 12 blade clearance probes, and 7 rate gyros were installed. Laser proximity probes measured fan and high-pressure turbine clearances. High-pressure turbine thermocouples also were used. Actual flight loads were measured as encountered during both aircraft acceptance tests and normal airline revenue service operations. Pressure taps measured aerodynamic loads. Gravitational and gyroscopic forces on the airplane center of gravity, the wing/strut intersection, and the engine were measured with accelerometers and rate gyros.

The findings from the NAIL project were as follows:

1. Aerodynamic loads on the nacelle are the prime cause of cold section clearance closure and rubs.
2. Aerodynamic loads are functions of nacelle angle of attack, air speed, and fan airflow rate.



Loads applied to the JT9D engine during X-ray tests.



The no. 1 Boeing 747 lifts off during the NAIL program to obtain flight data on the causes of engine performance deterioration.

Instrumentation aboard the no. 1 747 during the NAIL program gave it the appearance of a retail outlet as about 700 performance readings were monitored and recorded.

3. Aerodynamic loads, thrust, and differential thermal expansion cause hot section closure and rubs.
4. Inboard and outboard engines are equally affected by flight maneuvers.
5. A 0.7 percent increase in cruise thrust SFC is typical of production airplane acceptance testing.

The following recommendations were made:

1. Performance deterioration caused by flight loads and thrust bending will be minimized by integrated engine and nacelle designs that reduce loads on the engine cases.

2. Further development of exhaust path clearance control systems and abradable rubstrips will provide closer running clearance control in the turbine.

3. Use of 20 degrees flap (for the 747) at takeoff whenever possible will reduce aerodynamic loads on the inlet.

Clearance investigations on the CF6 high-pressure turbine and high-pressure compressor found most of the short-term performance loss to be due to rubs in the turbine. In the long term, about half of the performance loss in both the turbine and compressor was due to increased clearances. The high-pressure compressor is not refurbished as often as the high-pressure turbine. In addition, it was found that, with bore cooling in the compressor, clearances in the rear stages could be reduced by 0.04 inches, thus improving compressor efficiency by 0.78 percent.

Cost-effective feasibility studies were conducted as a part of the engine diagnostics project. At 1979 fuel prices, it was found that four-fifths of the 2 percent cruise SFC currently unrestored after each engine repair/overhaul would be cost effective to restore. In the CF6 fleet alone, a 1 percent gain in performance equals a yearly saving of 35 million gallons of fuel. It is becoming apparent to many airlines that additional maintenance activity on the engines to regain previously unrestored performance is cost effective, because fuel prices have risen faster than prices for other factors and now represent about 60 percent of an airline's direct operating costs.

The diagnostics program revealed short-term performance deterioration to be less than 1 percent cruise SFC. The causes are either flight loads (particularly in the JT9D) or thermal mismatches (in the CF6) that result in rubs between blade tips and stationary shrouds. Long-term performance loss occurs gradually and is about 2.5 to 3 percent cruise SFC (including initial short-term deterioration) after 2500 to 3000 flights. This long-term loss is associated with more severe rubs, airfoil quality degradation, and parts distortion. Cold section refurbishment has surfaced as a very important area for airline attention—previously most of the work was done in the hot section. In addition, the results will be used to design far better performance retention in future engines.

Deterioration has been found to be more dependent on the number of flight cycles, flight cycle length, and amount of reduced thrust operation than on the length of time the engines are operated. The cores of the engines (the high-pressure turbines and compressors), as predicted, still account for about 66 percent of performance loss. The new information acquired from the ACEE ECI program ensures benefits for the next generation of engines and makes possible fuel savings in engines currently in use.

Chapter 3
Energy Efficient Engine

In the early 1970s NASA was interested in what it called the fuel-conservative engine. When the ACEE program was funded, the concept was incorporated into the project and renamed the Energy Efficient Engine (EEE, or "E cubed" for short).

As in many NASA programs, the goal of the EEE project is to provide a technology base, first by proving a concept and then by testing and evaluating it under controlled conditions. The specific role assigned to EEE was to lay the advanced technology foundation for a new generation of fuel-efficient turbofan engines, with technology readiness by 1984. A balanced set of goals for fully developed and flight-qualified engines was established from the beginning to guide the technology efforts. Relative to current turbofan jet engines (specifically the GE CF6-50C and the Pratt & Whitney JT9D-7A), the NASA goals for EEE were:

1. Reduce fuel usage (SFC) by at least 12 percent and the performance deterioration rate by at least 50 percent.
2. Improve direct operating costs (DOC) by at least 5 percent.
3. Meet future Federal Aviation Administration regulations and Environmental Protection Agency exhaust emission standards.

A turbofan engine, unlike early turbojets, uses an extra set of rotating blades, placed ahead of the working core of the engine like a small enclosed propeller. The fan—that extra set of blades—is driven directly by power from the turbine. The fan propels the entering air stream, part of which goes through the core and the remainder around the outside of the engine, bypassing the core. The turbofan bypass ratio is the ratio of the amount of bypass air to the amount of air going through the core. When that ratio is around four or five, the engine is called a high bypass ratio engine.

Turbofans have evolved into very efficient engines compared with the earlier turbojet and the low bypass ratio fan engines developed in the 1950s and 1960s. High bypass ratio turbofans power the new generation of wide-bodied transports and show a potential for further development.

Under the ACEE program, NASA Lewis contracted with General Electric and the Pratt & Whitney Aircraft Group of United Technologies to explore this potential through two parallel EEE contracts, each consisting of three major activities:

1. Design of the basic propulsion package, called the Flight Propulsion System (FPS), to serve as the basis for defining the component configuration and technology advances to be evaluated in subsequent phases.
2. Investigation of component technologies—full-scale design, fabrication, and testing of most of the advanced components.
3. Integration of the advanced component designs into engine systems for experimentally assessing performance as a working unit and evaluating the various advanced systems technology features in a real-world environment.

Although each company was directed to build an engine to demonstate and evaluate the advanced technology concepts in an engine environment, the contracts were not for purposes of building an engine that could be considered ready for production. Incorporation of any or all of the EEE technology into future production engines was left to the engine manufacturers, to be accomplished when all the technology was sufficiently established to warrant such a step and when the market for a new or modified, advanced, fuel-conservative engine was judged to be appropriate.

From the beginning of the EEE program, both General Electric and Pratt & Whitney decided to enter areas in which they had not been traditionally involved. This "clean sheet" opportunity gave both companies the chance to leave their normal line of evolutionary development and leap forward into high-risk (yet high-potential) areas of research to aggressively push the frontiers of technology. With the ACEE program serving as an impetus to industry, not only here but in all six program areas, a good five-year-plus jump in technology is the result.

Candidate engine configurations and cycle conditions were selected by each engine manufacturer during preliminary engine definition studies with the aid of Boeing, Douglas, and Lockheed (as subcontractors) in airplane/mission definition and engine/airframe integration. Pan American and Eastern Airlines gave "real-world" user input through NASA.

Both engines emerged with two spools and a total inlet airflow of about 1,400 pounds (635 kilograms) per second, a bypass ratio of about 7, a long duct nacelle with exhaust mixer, and a takeoff thrust of about 36,000 pounds. A direct drive, as opposed to a gear-driven, fan was chosen for both engines—the same basic configuration as the CF6-50C and JT9D-7A engines, which served as the comparison or baseline engines. Overall pressure ratios are 50 percent and 20 percent higher than those of the baseline engines for the Pratt & Whitney and General Electric designs, respectively, and both are designed for higher turbine inlet temperatures for improved fuel economy. Although the overall configurations and cycles for both energy efficient engines are similar, each contractor employed unique component and system designs incorporating different technologies.

Estimates of the improvement in SFC over the baseline engines are between 14 and 15 percent, exceeding the 12 percent goal. Over half of the anticipated SFC improvements are a result of improvement in component efficiencies. The remainder come from work on engine cycles and mixer nozzles. It appears that the other goals will be met as well.

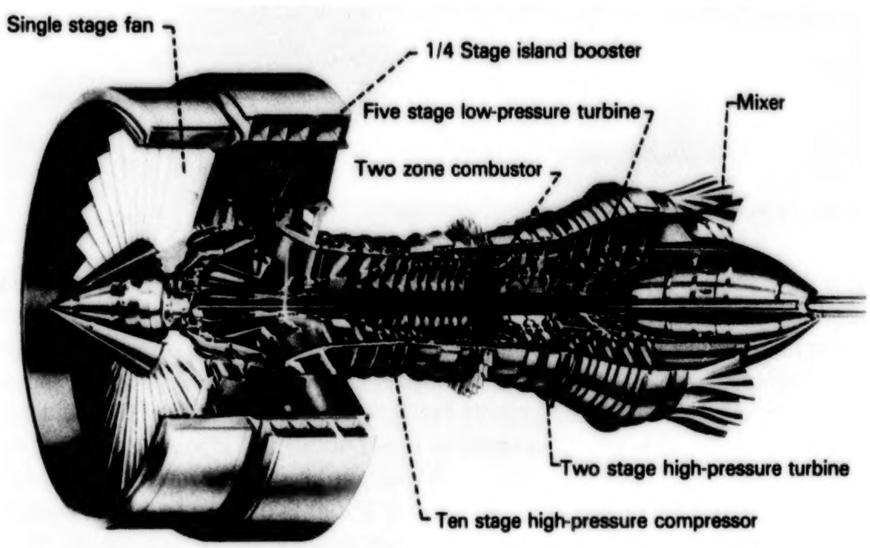
During the first two years of the project effort, both FPS designs were completed, including the engine components, nacelle, exhaust-gas mixer, engine control system, and engine accessories. These designs represent the current views of both General Electric and Pratt & Whitney on the technology requirements of the next generation of turbofan engines.

GENERAL ELECTRIC

General Electric's EEE configuration has two corotating spools and employs only two main frames. The base engine length is about 10 percent shorter than a CF6-50 scaled to equivalent thrust level, and the nacelle around the engine is a slender, low-drag design. Mounting the accessory package inside the core cowl allows for a low nacelle frontal area, with resulting lower drag. Bulk absorber type acoustics are used in the inlet, inner and outer walls of the fan duct, and aft of the low-pressure turbine at the end of the core flow passage. The nacelle includes a fan-stream thrust reverser totally encased in the outer structure with no actuation links in the fan bypass stream.

The fan is a single stage, low tip speed, high bypass ratio design. Solid titanium blades incorporate a single shroud located at about 55 percent span and

General Electric's EEE configuration.



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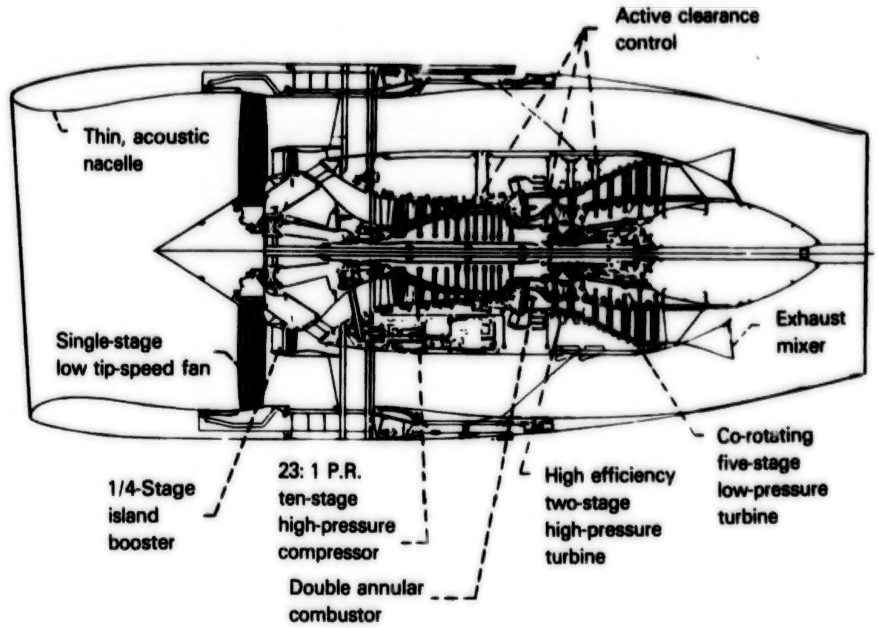
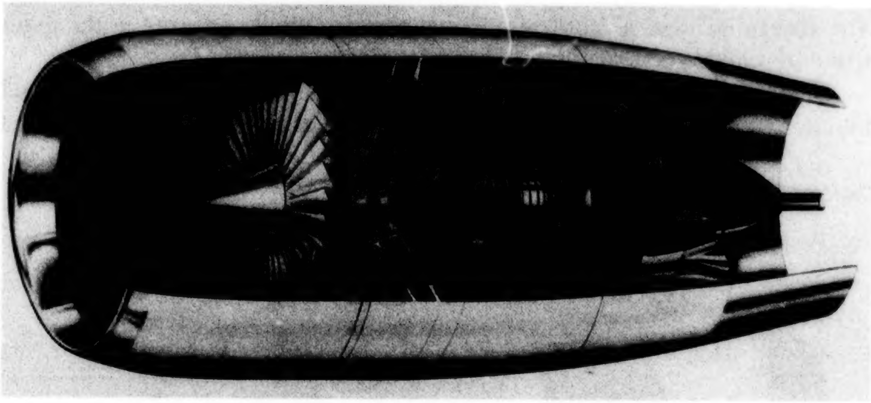
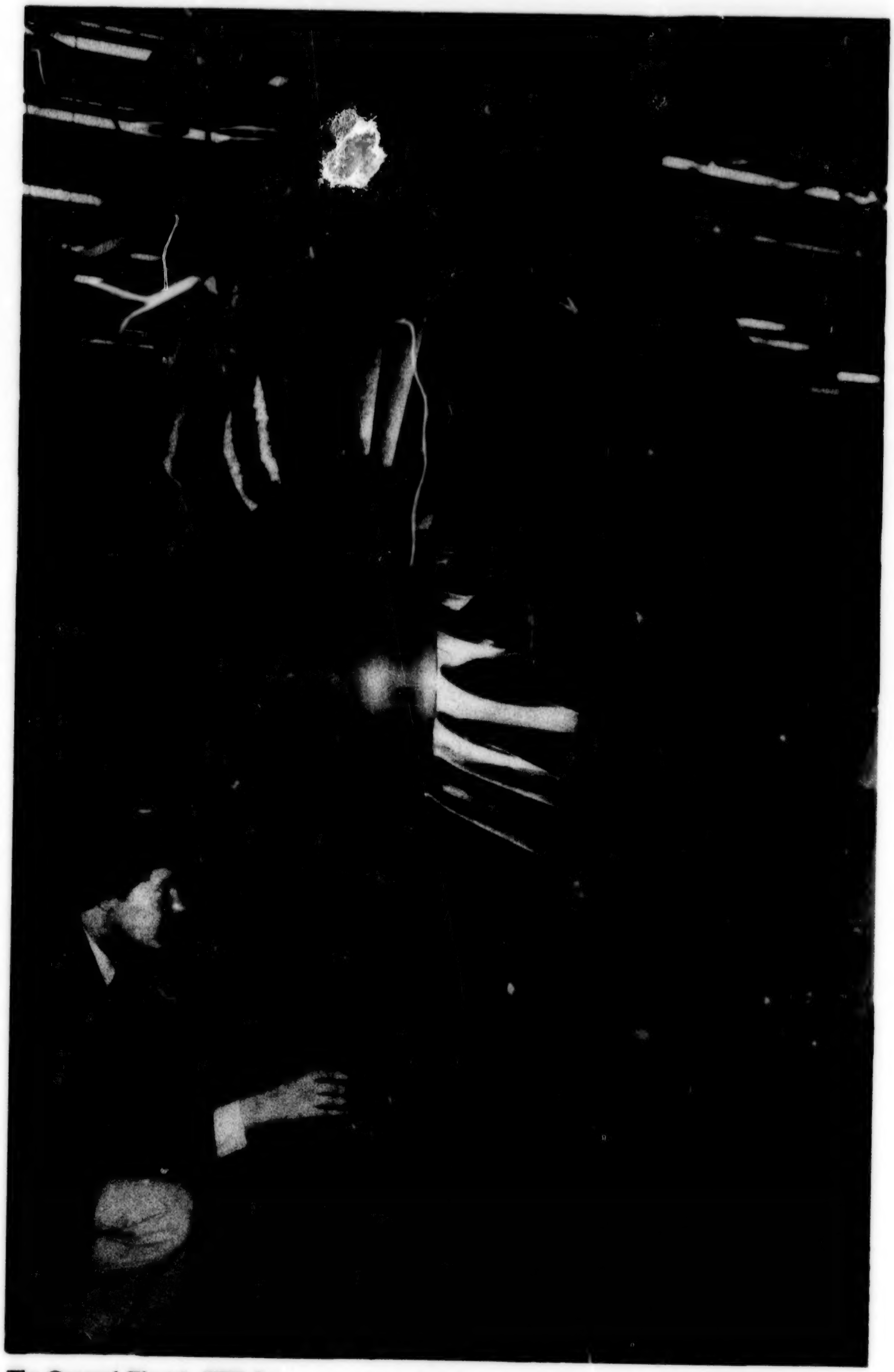




General Electric's EEE configuration (continued).

near the trailing edge (as in the ECI program) to minimize aerodynamic losses. A composite frame is featured, wherein the vanes are integrated with the support struts to minimize the number of airfoils, reducing fan frame weight and cost.

The integral vane-frame design requires that the vane/struts be large enough to provide adequate support but few enough in number to avoid excessive blockage. This results in about an equal number of blades and vanes. To offset the increased noise associated with this combination, the axial spacing between vanes and blades has been increased to about two chord widths. The inlet is cantilevered from the fan-frame and is independent of the fan casing. As a



The General Electric EEE fan.

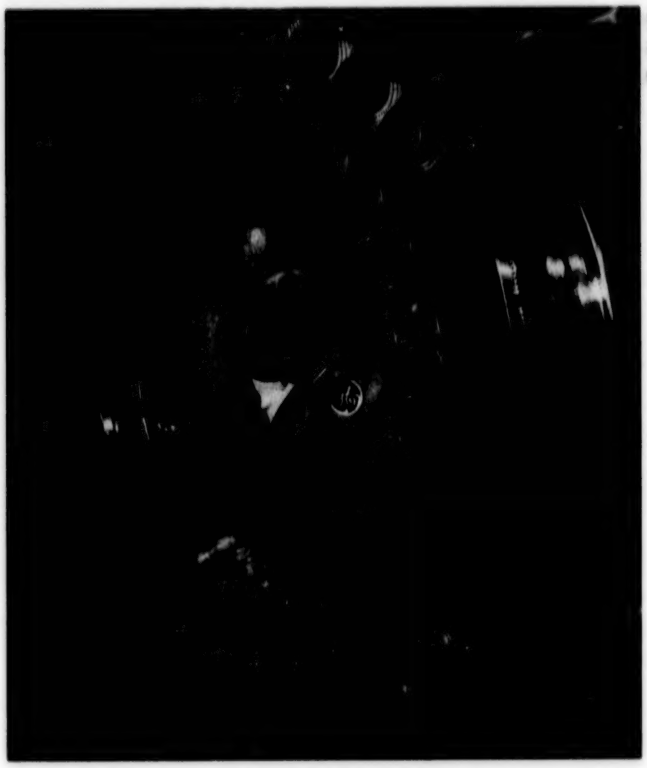
result, the fan casing is not subject to any flight loads. This allows tighter clearances in the fan and subsequent performance increases. A quarter-stage island booster behind the fan duct allows excess core flow to be diverted into the fan duct for automatic core-flow matching—it also acts as a foreign object separator, throwing dirt and other particles outward and back into the bypass stream and away from the engine core.

The compressor, the major area of innovation for General Electric, is aimed at achieving a pressure ratio of 23:1 in only 10 stages by using highly loaded, low aspect ratio, rugged airfoils. It has four variable-vane stages and a variable inlet guide vane. Active clearance control is employed on the last five stages to achieve tight-running clearances by passing cooler, front-stage bleed air over the rear compressor case to control its thermal expansion. Climb, and particularly cruise, performance increases as a result. The low number of stages allows a shorter, stiffer compressor that is less subject to deflections and resulting performnace deterioration.

The double-annular combustor was designed by General Electric for low emissions and was an outgrowth of the NASA Experimental Clean Combustor Program. A segmented, or "shingled," liner is utilized to provide increased life and low maintenance; the split-duct diffuser divides the flow for the two concentric burning zones, permitting a very short combustor length. In the EEE combustor, with only half of the cooling airflow compared to current combustor designs, a threefold increase in burner life is expected due to the segmented design, which reduces the thermal stresses of rapid heating and cooling cycles.

The high-pressure turbine is a high-efficiency, two-stage design, both stages incorporating high tip speeds, with only modest increases in turbine temperatures. Active clearance control is achieved as fan air is allowed to

The major breakthrough for General Electric's EEE is the 10-stage high-pressure compressor which gives a 23:1 pressure ratio. The forward case assembly encloses the rotors.



General Electric's combustor ring looks complicated due to emission requirements.

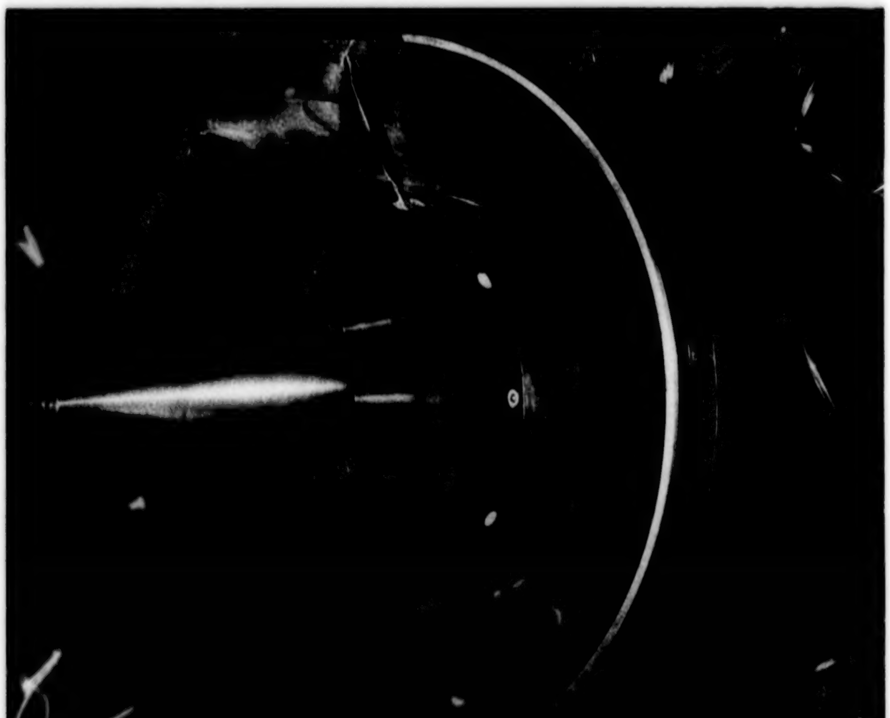
General Electric's two-stage high-pressure air turbine.

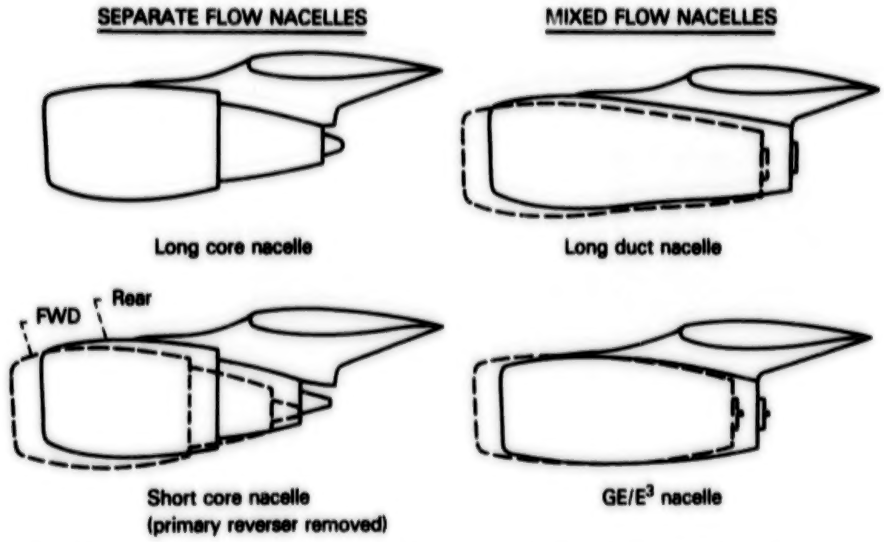
impinge on the turbine case. The two-stage turbine itself is cooled by means of compressor discharge and interstage air for the vanes and blades, respectively. A major design result is the substantially extended life obtained through use of advanced directionally solidified airfoil material, a ceramic shroud over the first stage rotor, advanced powder metallurgy disks, and elimination of bolt holes in the disks. Cooling air requirements have also been reduced through the use of advanced turbine materials.

The low-pressure turbine has five uncooled, highly efficient stages, acoustically tuned to reduce noise. Improved performance is achieved by reducing pressure losses, improving the aerodynamic design, and using active clearance control. A short transition duct between the high-pressure and low-pressure turbines permits high blade velocities in the initial stages, with lower overall average blade loading.

General Electric's gas mixer is a long duct, mixed flow design. The hot core engine stream is mixed with the cooler fan bypass stream through an advanced

General Electric's mixed flow exhaust nozzle. The mixer design reveals some rethinking about keeping engine bypass and exhaust air separate. Mixing the two has shown an improvement in fuel efficiency.





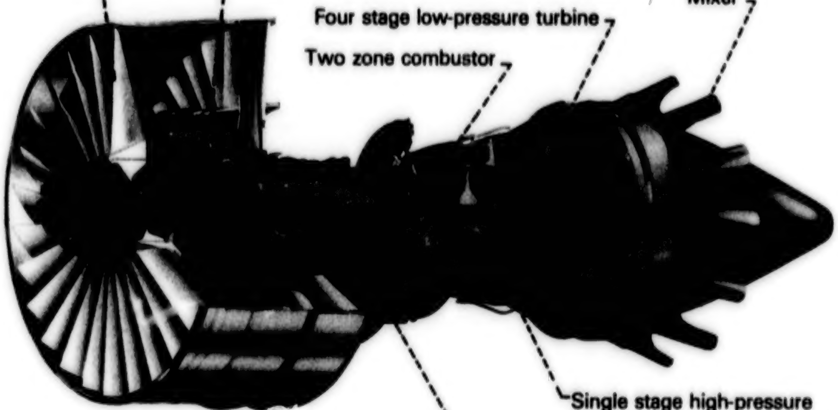
These General Electric nacelle configurations were installed and tested at the Langley Research Center on an Energy Efficient Transport model.

lobe-shaped mixer and then expanded through a mixed-flow exhaust nozzle. The 12-lobed mixer and the mixing chamber are short in length to minimize weight, internal pressure losses, and external nacelle drag. The overall objective is to generate a design that effectively mixes the core and fan flows in a relatively short length, keeps any pressure losses to a minimum, and is relatively lightweight. Designers have to be careful that the added weight of a mixed flow system and/or the drag of the long-duct nacelle does not offset the gains from the mixing. This nacelle and several other current technology nacelles have been tested at NASA Langley under a supercritical wing on an Energy Efficient Transport half-span model. In a forward position, relative to current installations, the EEE nacelle drag was quite low. With careful tailoring of the wing/pylon/nacelle combination, the installed drag of the long-duct nacelle can be comparable to a conventional separate flow nacelle.

A comparison of the General Electric EEE with the CF6-50C shows a much higher bypass ratio, whereas the fan pressure ratio is slightly lower and the compressor pressure ratio is almost double. Overall, the EEE FPS design has a 38:1 pressure ratio and a 100°F turbine temperature increase, to arrive at a projected SFC 14.2 percent lower than that of the CF6-50C at maximum cruise. A DOC reduction ranging from 5 to 12 percent would result from this SFC reduction.

PRATT & WHITNEY

Pratt & Whitney's two-spool, mixed-flow engine has two major frames with both main shaft bearing compartments situated between the compressors

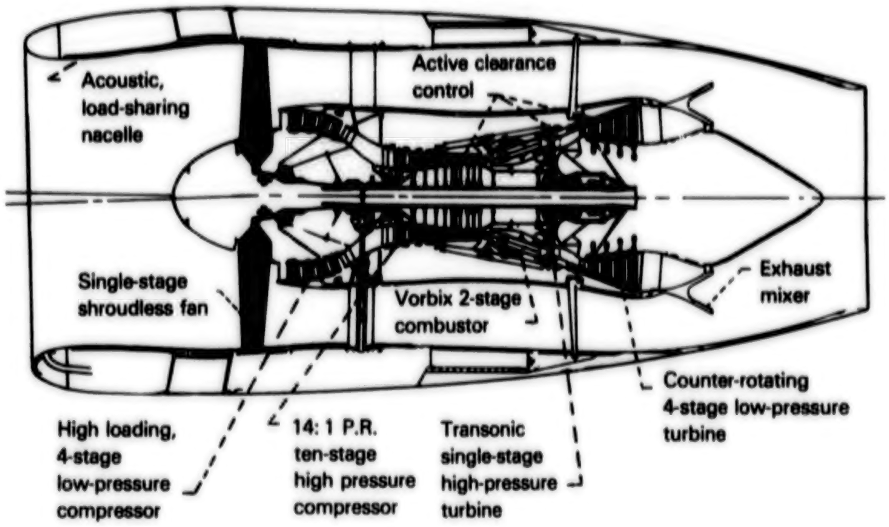


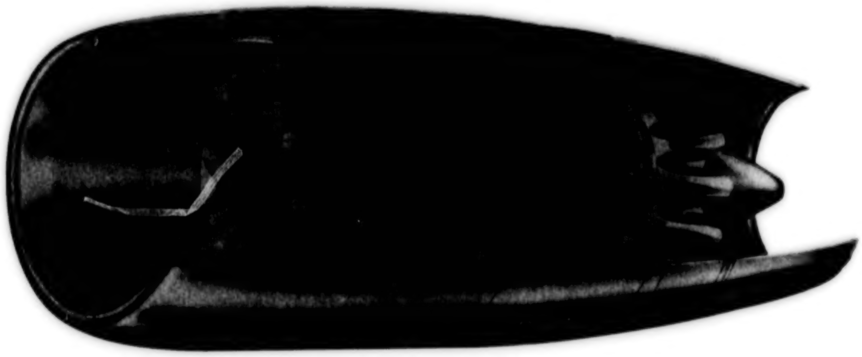
Pratt & Whitney's EEE configuration.

and between the turbines to independently support the counterrotating rotors. The nacelle has extensive acoustic treatment throughout the inlet and exhaust ducts. Through a concept called cowl load sharing, the fan ducts are designed to transmit much of the inlet gust load and other cowl loads around the engine case to the engine mounts, reducing case deflections.

For the Pratt & Whitney EEE fan, designs for both a shroudless, hollow titanium fan blade and a shrouded solid titanium fan blade were investigated; the latter was finally selected as a better compromise among performance, weight, and risk. The shroudless hollow blade design, with its potential for better performance, was still heavy relative to a normal shrouded fan. Significant fabrication problems were experienced as well. Additional technology development beyond the timing of the EEE program will be required to prove this concept. The fan exit guide vanes are integrated with the duct structural struts to reduce engine weight and cost. The spacing between the fan blades and exit guide vanes was increased to provide a low noise configuration.

The 4-stage low-pressure compressor and the 10-stage high-pressure compressor use controlled diffusion airfoils and low-loss endwall concepts to raise efficiency levels. Efficiency was further increased through the use of rotor tip trenches and reduced tip clearances. Active clearance control is accomplished by ducting fan air through impingement tubes onto the high-pressure compressor case. Lower aspect ratio blades and vanes reduce the number of airfoils to almost half, reducing maintenance costs. The concept offers higher pressure per stage, higher efficiency, improved performance retention, and lower maintenance costs.





The staged combustor, again an outgrowth of NASA's Experimental Clean Combustor Program, has two in-line combustion zones to control emissions. The overall length of the combustor has been reduced by the use of a short, low-loss, cusp-type diffuser section. A segmented liner to increase combustor liner life, as well as to reduce cooling air requirements, is held in place by a frame structure that surrounds the outside.

To obtain a large reduction in number of airfoils, initial cost, and engine maintenance costs, a single-stage, highly loaded, high-speed, high-pressure turbine was incorporated, using transonic aerodynamics. Single-crystal alloy, highly twisted and cambered airfoils were designed to reduce cooling airflow requirements. The long chord vanes and highly twisted blades are significantly larger than state-of-the-art single-crystal vanes and blades. Ceramic outer air seals permit the use of tighter rotor tip clearances and reduce cooling re-

quirements. Active clearance control is utilized to minimize the clearance during cruise while avoiding rubs during takeoff and climb.

The four-stage low-pressure turbine using low-loss airfoils requires no airfoil cooling and counterrotates relative to the high spool, permitting lightly loaded low-pressure turbine inlet vanes for increased turbine efficiency. Active clearance control is used in both the high- and low-pressure turbines through internal case air cooling to minimize rotor tip clearances during cruise.

The 18-lobe, scalloped, high-penetration exhaust mixer is designed to provide high mixing efficiency with a relatively short mixer and mixing chamber. As with the General Electric design, the short length minimizes pressure loss, weight, and external nacelle drag.

Cycle parameters for the Pratt & Whitney EEE FPS design, compared with the JT9D-7A (at maximum cruise), show the EEE cycle with a higher bypass ratio and fan pressure ratio plus a significantly higher overall pressure ratio. Turbine temperatures are about 200°F hotter. Projected cruise SFC indicates a 15.1 percent improvement.

The major mechanical design features aimed at reducing performance deterioration in the EEE engines at General Electric and Pratt & Whitney are erosion-resistant coatings, thick leading-edge airfoils, reduced rotor and case deflections under load, active clearance control, and abradable rub tips.

Since the major contribution to SFC improvement of the EEE designs will be achieved through performance improvements in each of the major engine components, the primary emphasis has been on the development of component technologies. Full-scale testing of major engine components was initiated by each company to demonstrate predicted performance levels. The components were to be built into engine systems, called the core and integrated core/low spool (ICLS), to experimentally assess the integrated performance of the components and the advanced systems technology features.

Assuming continuance of the ACEE program through the end of its projected time frame with technology readiness demonstrated by 1984, a new generation of fuel-conservative engines could be introduced into airline service by the late 1980s or early 1990s. By the year 2000, the rising price of fuel is expected to account for around 82 percent of airline DOC versus 60 percent at present.

If the EEE designs had been started under the present fuel price environment, there probably would be even more emphasis on absolute fuel savings and less on reduced maintenance costs. The crucial area of research, without question, has become fuel economy. Estimates of the full SFC potential of the EEE designs, should they be taken beyond their present state, range between 19 and 21.5 percent. To realize this, both contractors would specify bypass ratios in the higher 7 to 7.5 range. Pratt & Whitney would add an additional stage to both the high-pressure and low-pressure turbines, whereas General Electric suggested an overall cycle pressure ratio increase, up to 45:1, and reduced turbine cooling requirements.

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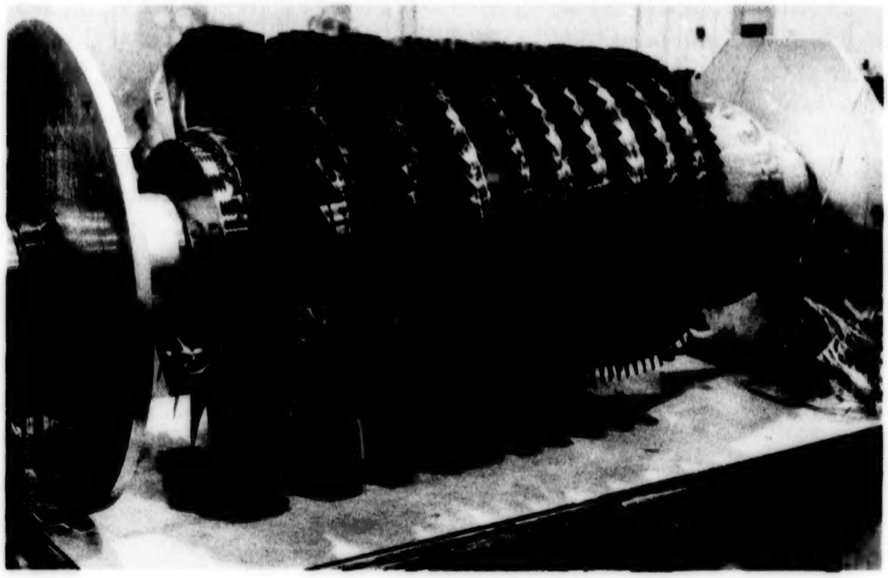
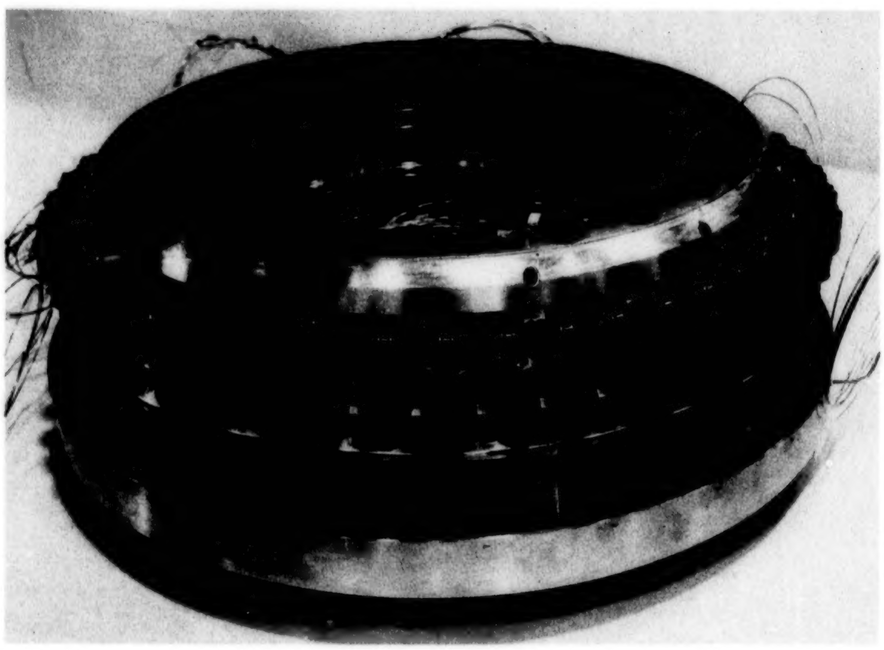


Pratt & Whitney's EEE high-pressure compressor rotor assembly.

Pratt & Whitney's annular two-zone combustor in the final stages of assembly.



There is promise in further research with geared turbofans and the prop-fan or Advanced Turboprop (ATP). The ATP has been funded under the ACEE program (see Chapter 4), and it appears to offer far more potential fuel savings than does a geared turbofan.

Both General Electric and Pratt & Whitney have expressed enthusiasm for the EEE program. It has enabled them to press ahead on futuristic research without very high economic risk. The companies see themselves in the precarious position of not being able to afford to stand still while not being able to afford to fail. EEE has helped keep American engine technology at the forefront of the world market.

Chapter 4
Advanced Turboprops

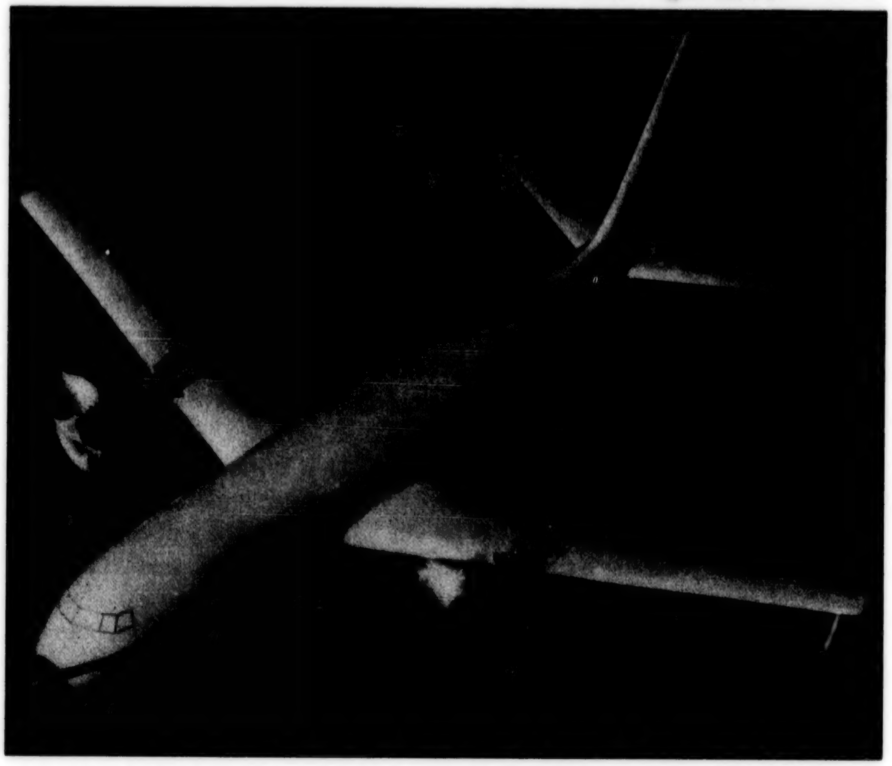
The reemergence of the propeller for future propulsion of high-speed commercial air transports has been viewed by many as a step backward, with more than two decades of commercial jet transport service behind us. However, there are very good reasons to reconsider the propeller, which have to do with fuel economy.

At speeds below the speed of sound (Mach 1), it is more efficient to move an airplane through the air with a propeller than to thrust it along by a turbofan or turbojet engine. Indeed, one reason for the relative efficiency of the turbofan engine is that it is basically a turboprop engine with a shrouded, small-diameter, high-speed propeller.

Efficiency, roughly stated, is the ability of a propulsion system to convert the energy created by the power plant into forward thrust. The installed propulsive efficiency of a high bypass turbofan is about 60 percent at Mach .60, rising slowly to near 65 percent at Mach .80 (the basic cruise speed of modern large transports). In comparison, even the older 1950s-era turboprops were 80 percent efficient at Mach .62 (the Lockheed Electra's cruise speed). Unfortunately, older turboprops were not efficient at Mach .80 flight speeds. Now, however, the newer, high-speed, advanced turboprops (called prop-fans), are about 85 percent efficient at Mach .60 and about 80 percent efficient at Mach .80—a 15 percent improvement over the turbofan.

This efficiency advantage, if it can be maintained through installation, translates into a flight-averaged fuel saving of 20 percent over an aircraft powered by equal technology turbofans. Using a modern technology gas turbine drive, a prop-fan aircraft could show a 60 percent saving over current jet aircraft such as the early DC-9s and Boeing 737s and a 40 percent saving over older turboprops like the Convair 580.

The original propeller-powered airplanes used piston engines. In the 1950s, the gas turbine engine replaced the older piston engine, producing the first turboprop. This combination seemed to be ideal for the flight speeds of the day—420 miles per hour, or Mach .60, which was quite respectable. Prop-driven aircraft also provided higher takeoff and reverse thrust, thereby shortening runway requirements. Turboprops, with their higher rates of climb and descent, provided lower community noise levels. However, when cruise speeds rose beyond Mach .60, propeller efficiency fell drastically.



The transport of the future could very well have propellers.

By 1955 the turboprop began to lose favor, not only because the jet-powered aircraft cruised faster, but because jets had lower maintenance costs, lower vibration levels, greatly reduced cabin noise, increased seating capacity, and lower ride roughness because they had higher cruising altitudes. A jet could also "get out of the weather," or at least most of it, compared to prop-driven aircraft. Simply put, jets were larger, carried more people, and flew faster with fewer mechanical problems, a combination that easily compensated for their increased use of (cheap) fuel.

Propellers, however, continued to challenge the minds of a few engineers. Researchers explored high-speed propellers, with thin, swept blades. The sweep of a blade helps to avoid compressibility problems in much the same way a swept airplane wing does—by delaying shockwave buildup. An added benefit of blade sweep is reduced propeller-generated noise.

In the 1950s researchers built and wind tunnel tested some of the advanced propeller models, but the material and structural design technology of the time could not handle the radical shapes and thinness of the new blades. More important, manufacturers and operators were already proceeding with the develop-

ment of turbojets that not only did away with the large, cumbersome props, pitch change devices, and gearboxes, but also provided Mach .80 speeds immediately. Who cared that the jets gulped greater quantities of fuel when the price was below 10 cents a gallon?

By the 1970s and early 1980s, fuel efficiency was more important. Since the 1950s, the cost of jet fuel had gone up more than 1000 percent and all forms of fuel efficiency were being considered. Advanced turboprops were placed high on the NASA priority list, based on initial investigations in 1973 and 1974 under the RECAT (Reducing the Energy Consumption of Commercial Air Transportation) studies. During the early work, a small group of technical specialists at NASA's Lewis Research Center and at Hamilton Standard, one of the leading propeller manufacturers, resurrected the advanced high-speed propeller. They proposed a propeller with many thin, swept blades, which they nicknamed "prop-fan," and which looked more like some household fans or carnival pinwheels than anything else. These propellers resembled the high-speed props abandoned in the late 1950s.

From the beginning of the ACEE program in 1976, the Advanced Turboprop (ATP) project was included as one of the six areas of research. Its objective was to provide the technology for the efficient, reliable, and acceptable operation of an advanced turboprop aircraft at cruise speeds up to Mach .80 and altitudes up to 35 000 feet. The goal was a 15 to 20 percent fuel saving relative to comparable technology turbofan aircraft, while maintaining cabin comfort (noise and vibration) equivalent to current turbofan-powered aircraft. A technology readiness date of mid to late 1980s was reestablished for a "first generation" of advanced turboprops.

Resurrecting the propeller was not going to be easy. With the focus on jets from 1955 to 1975, there was a 20-year void in high-speed propeller research. At the higher subsonic speeds proposed, major uncertainties still existed in the areas of propeller acoustics, propeller efficiency, propeller structures, installation-related losses, cabin noise and vibration levels, and gearbox capability. It was clear that an advanced turboprop was a systems problem—all the potential drawbacks would have to be solved for it to work.

NASA formally initiated ATP in 1978 with management at the Lewis Research Center, originally in three phases.

In phase I (1978 through 1980), Enabling Technology, a fundamental performance data base for the thin, swept-tip, multibladed, high-speed propellers was established through test and analysis of several small-scale propeller models in wind tunnels at Lewis and the United Technologies Research Center. In addition, analytical and experimental investigations were conducted in the areas of fuselage acoustics and installation aerodynamics.

In phase II (1981 through 1985), Large-Scale Structures, emphasis went from small-scale model work to the design, fabrication, and ground testing of large-scale (8- to 10-foot diameter) propellers. Work was also to continue in the

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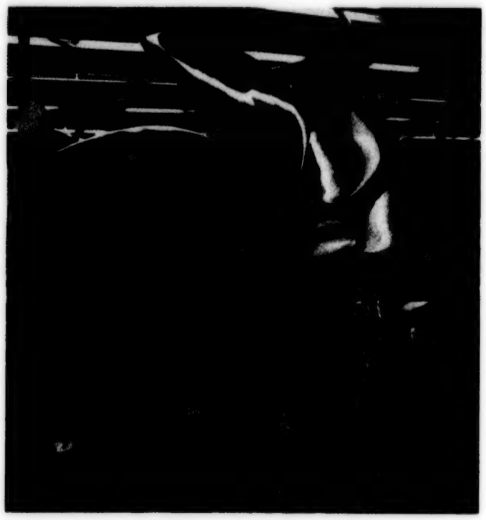
A new shape for the sky? One of the several Hamilton Standard test propellers in a wind tunnel.



A test propfan under construction at Hamilton Standard.

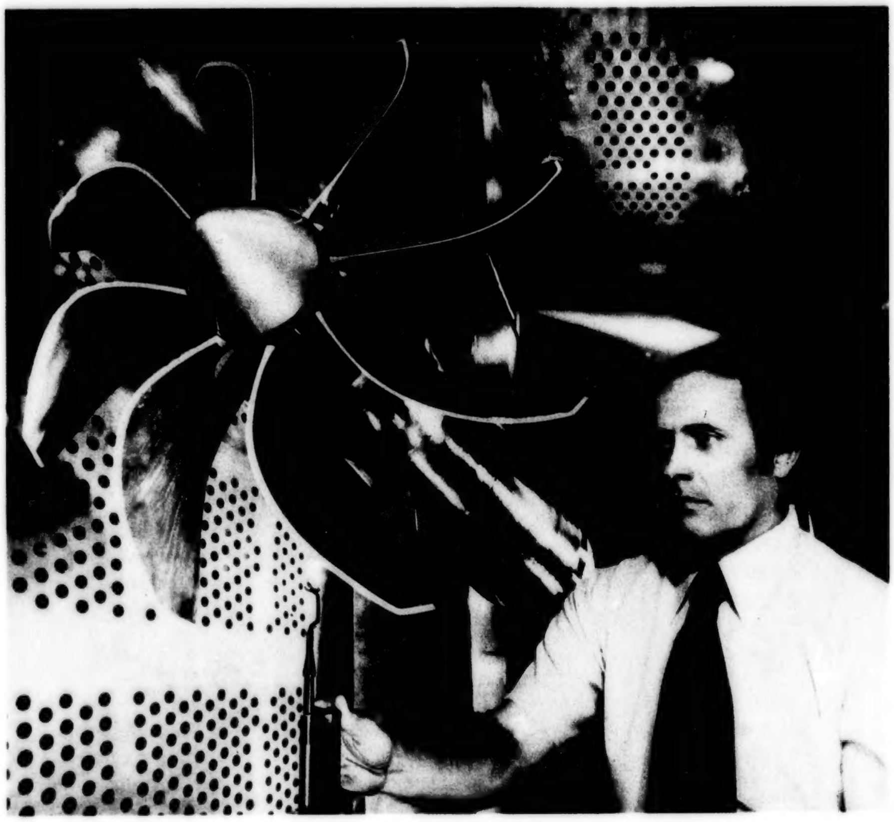
One of the early propfan propellers being tested on the Energy Efficient Transport wing in a Langley wind tunnel.

areas of fuselage acoustics and installation aerodynamics, focusing on providing the aircraft integration information required for properly configuring a flight research aircraft, to be assembled and tested in phase III of the project.

The decisive phases, II and III, were aimed at placing a large-scale (8- to 10-foot diameter) propfan in the real world of flight testing. The hurdle of budget constraints must be cleared before the final steps can be completed.

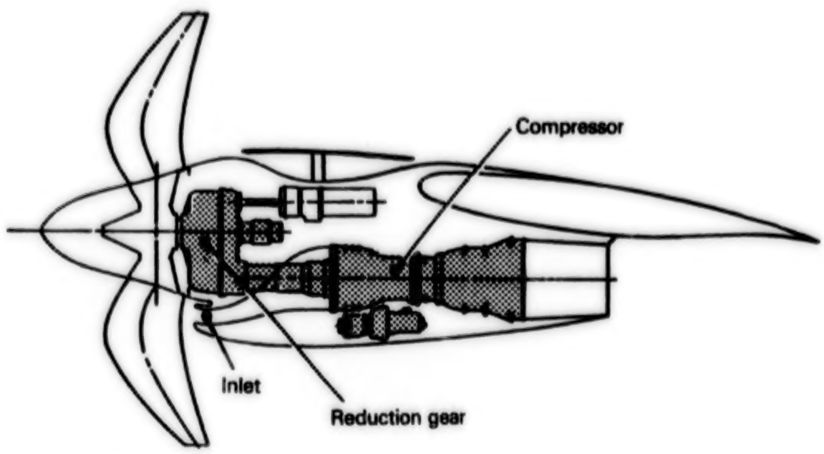
PROPELLERS

Wind tunnels have demonstrated the propeller efficiency goal of 80 percent. Hamilton Standard, under ATP's phase I, produced examples of three eight-blade models, a straight-tip model, an aero/swept-tip model, and an aero/acoustic swept-tip model, each designed to operate at Mach .80 at 35000 feet. The models were distinguished primarily by the difference in blade geometry relative to blade twist and the degree of aerodynamic sweep near the blade tips.

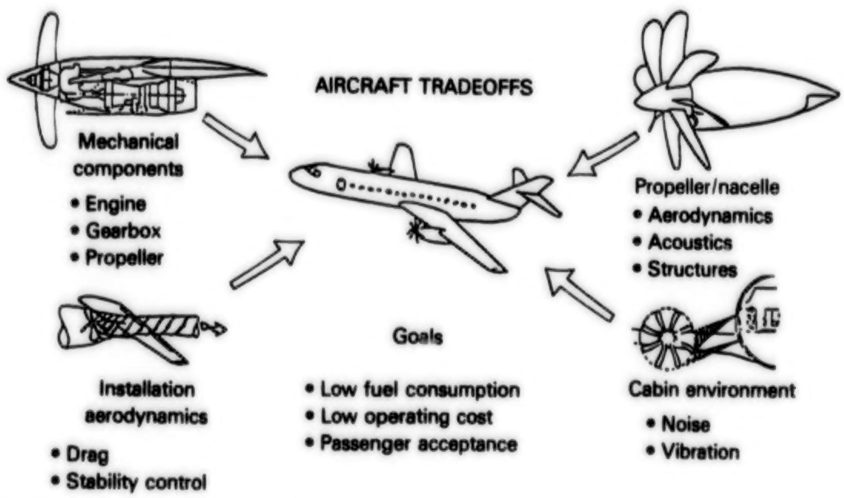


This eight-blade propeller was tested in the wind tunnel at NASA's Lewis Research Center. Its swept blades were found to be more efficient and less noisy than previous turboprop designs.

Another challenge is the integration of the propeller with the wing design to achieve the best combination of efficiency and aircraft lift-to-drag ratio. Phase I attempted to address this issue, but there is still much hardware testing needed, since large-scale propfan systems will not work in any existing wind tunnel for proper test simulations because of tunnel wall interference. Engine drive, gearbox, and prop construction must be proven as well. Inlet-engine compatibility and acceptable cabin noise levels, along with acceptable maintenance and reliability are also problems that must be solved.



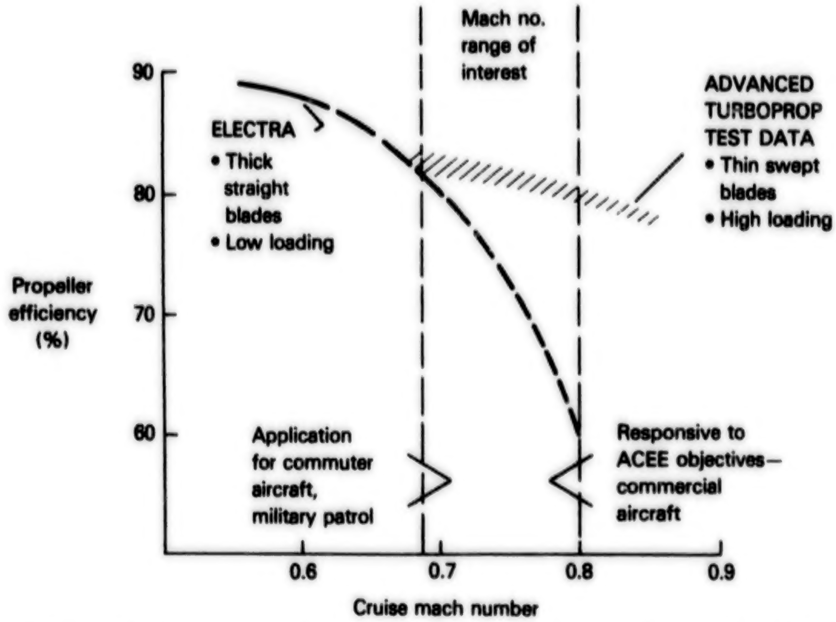
Propfan engine areas requiring added technology work to qualify for integration into an effective propulsion system.



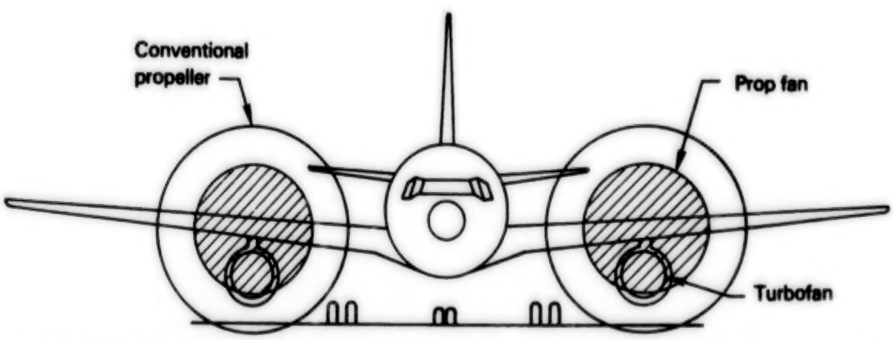
The challenge before propfan designers. Large fuel savings are possible if all these aspects of technology integration can be worked out successfully.

When phase I ended, a fundamental high-speed propeller data base had been gathered, along with key analytical and experimental investigations into fuselage acoustics and installation aerodynamics.

Boeing, Douglas, Lockheed, Detroit Diesel Allison, Pratt & Whitney, and General Electric were brought into ATP to begin researching the problem from their respective areas of expertise. Although doubts surfaced at various points, each company has made studies of aircraft and core engines that could utilize the propfan.



Propeller efficiency versus speed shows the drastic improvement the propfan will have over the Lockheed Electra of the 1950s.



A significant side benefit of swept blades on the propfan is decreased prop diameter. This will allow integration of the system to smaller transports without modification of landing gear or other clearance requirements.

The first flight tests with a model propeller were carried out on NASA's JetStar at the agency's Dryden Flight Research Center, Edwards, California. The Lockheed jet was outfitted with a pylon-mounted propfan installation and microphones on the outside of the fuselage, below the two-foot diameter model propeller, which was driven at 8000 rpm. Tests were conducted at speeds up to Mach .80. The noise proved to be as much as 5 to 7 decibels lower than predicted. The boundary layer air on the aircraft was measured to record interaction since it significantly attenuates noise.

NOISE

The internal acoustic problems of aircraft have been found to be more than just the noise that hits the outside of the fuselage shell from a rotating propeller. Structure-borne noise (not really "noise," but vibration frequency noise), transmitted through wing or tail structures, penetrates the interior of the fuselage and may be a major noise problem. Flight tests on a DeHavilland Dash 7 found that cabin noise in the plane of rotation with the two inboard engines shut down was the same as that with all four engines running.

Tests for fuselage acoustics were conducted at Lockheed-California on a static fuselage from a Swearingen Metro, which incorporated several double-wall concepts that can cancel out noise by vibrating "in tune." Prop wake tests were done on a Lockheed P-3. The vortex actually hit the wing like a hammer.

Another consideration is the impact that propeller noise has on the communities situated around airports at which propfan aircraft would operate. Fortunately, as blade sweep increases on the propeller, noise decreases. Before 1975 there was no data base for these acoustics problems, but phase I increased our knowledge.

A 10-blade propfan design is mounted for acoustics tests on the NASA JetStar at the Dryden Flight Research Center.

Propfan flight test on the JetStar.

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ENGINES

Pratt & Whitney, Detroit Diesel Allison, and General Electric have addressed the engine/gearbox problems. Studies have found that advanced turboprop engines and turbofans with similar cores will have similar maintenance costs. However, there is still a great deal to do in designing a gearbox that can handle 10 000–15 000 shaft horsepower, the amount needed for a full-scale propfan. Just as a large-scale flight test is paramount to prove the propeller, such a test is needed for the engine/gearbox since NASA and the companies involved have been developing their research and technology base after a 20-year void. For large-scale tests, a Detroit Diesel XT701 turboshaft engine, developed for the Army's heavy-lift helicopter program, or its commercial version, with a modified T-56 gearbox on it, could drive a 9.5-foot propfan.

The large-scale advanced propfan (LAP) is high on the list of requirements if the ATP is to reach the marketplace. In phase II the LAP will have blades that utilize a solid spar covered by a shell, giving good strength characteristics along with an ability to survive impact damage, erosion, and lightning strikes. A hub and blade retention system, pitch change mechanism, and pitch control would also be incorporated. The first assembly could be tested by 1985 and flight tested in 1987 if the program acceleration requested by Congress continues to be funded. Previous NASA planning for flight testing in 1988 was considered by some in the industry to be too late for the next generation of transports. The

second phase also includes ground-based rig tests of an advanced gearbox and pitch change system suitable for a 10000–15000 shaft horsepower class engine.

AERODYNAMICS

Other areas, such as the effect of wing sweep on a full-scale installation, must be investigated. Since the inboard blade will be closer to the wing, an increased excitation results. Although complex, the problem does not pose insurmountable obstacles. Transonic flow across the wing will also occur at Mach .80. Although this is not an unknown aerodynamically, the slipstream swirl effects from the propeller pose new problems that will have to be addressed. Propfan wake is much tighter and stronger than traditional prop wakes.

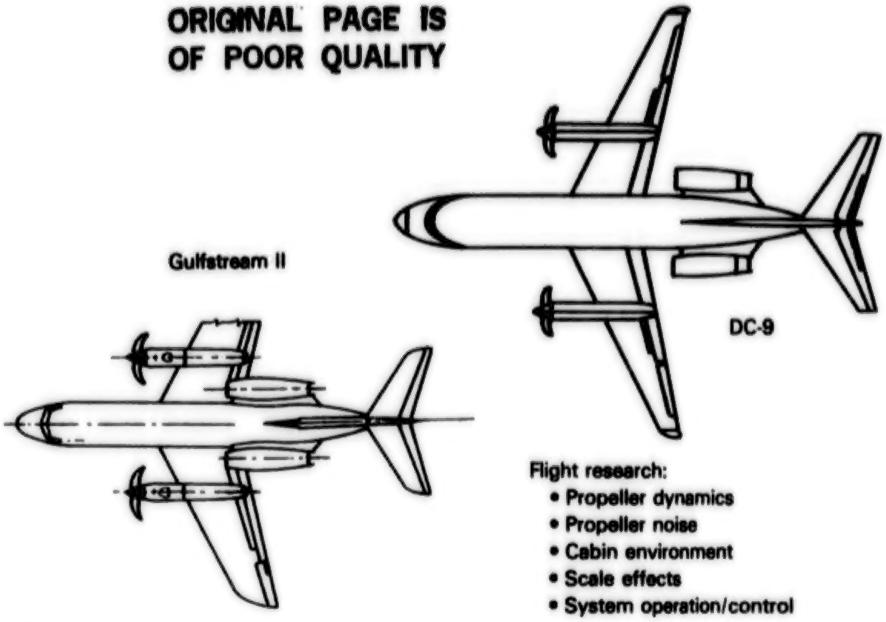
There is, quite simply, another dearth of data, since no studies on the effect of the propeller wake on the lift-drag of supercritical wings have been done (turbofans have always been pylon mounted as well, away from the wing) and there is no experience with pulsating, swirling, transonic flow through engine inlets. Engine response may vary with distortion of airflow. In addition, the effect of the propeller (location, wake, torque) on aircraft stability has not been evaluated at higher flight speeds.

In 1977 a Douglas propeller simulator was used in an Ames Research Center wind tunnel test program to determine the effect of a propfan slipstream on a high technology swept supercritical wing. The measured interference effects were less than predicted. In late 1980 and again in early 1982, NASA Ames conducted high-speed wind tunnel tests of a larger-scale model of the same wing configuration with a powered propfan installed, validating the initial findings and indicating that efficient installations are attainable. Langley has begun gathering a data base on ATP aerodynamic theory verification through engineering and model tests. Douglas, Lockheed, and Boeing have been conducting wing/nacelle computer code work, and Lockheed-Georgia has been doing analysis and design work on a core inlet for the engine.

The primary benefit from most of the research will be improved analytical codes for a technology base. Engineers and designers had to pick up from where things stopped in 1955, and the results have been gratifying. Now companies desiring to investigate ATP technology will have basic data and analytical methods with which to work.

TESTBEDS

Lockheed and Douglas have studied testbed aircraft to be used for large-scale propfan testing. Lockheed has suggested a Grumman Gulfstream II, whereas Douglas has recommended a DC-9-10. Either test aircraft would have one or two wing-mounted propfan installations, leaving the normal rear turbofan engines as primary power.



Large-scale propfan testing has been proposed for both the DC-9 and the Gulfstream II.

Since today's air transportation system has evolved around, even owes its existence to, turbofan-powered aircraft in use for 20 reliable, proven years, embracing the advanced turboprop as a replacement will require major rethinking. Neither commercial nor military developers can risk years of effort and billions of dollars for design, fabrication, and certification of new high-speed ATP aircraft and engines until the key technical issues are resolved and understood.

In summary, the technology issues are as follows:

1. Advanced high-speed propeller — performance-efficiency/noise; structures and dynamics.
2. Acoustics — cabin noise/vibration; community noise.
3. Installation aerodynamics — propeller/nacelle/airframe interactions, low drag, aircraft stability (including engine out performance); nacelle aerodynamics.
4. Mechanical components — modern gearbox; propeller pitch change/control.
5. Propeller/inlet/compressor compatibility — recovery/distortion/stability.

Of these, cabin noise/vibration, aircraft stability, nacelle aerodynamics, propeller pitch change/control, and propeller/inlet/compressor compatibility can be covered in the ATP program only if the level of program funding is allowed to increase significantly.

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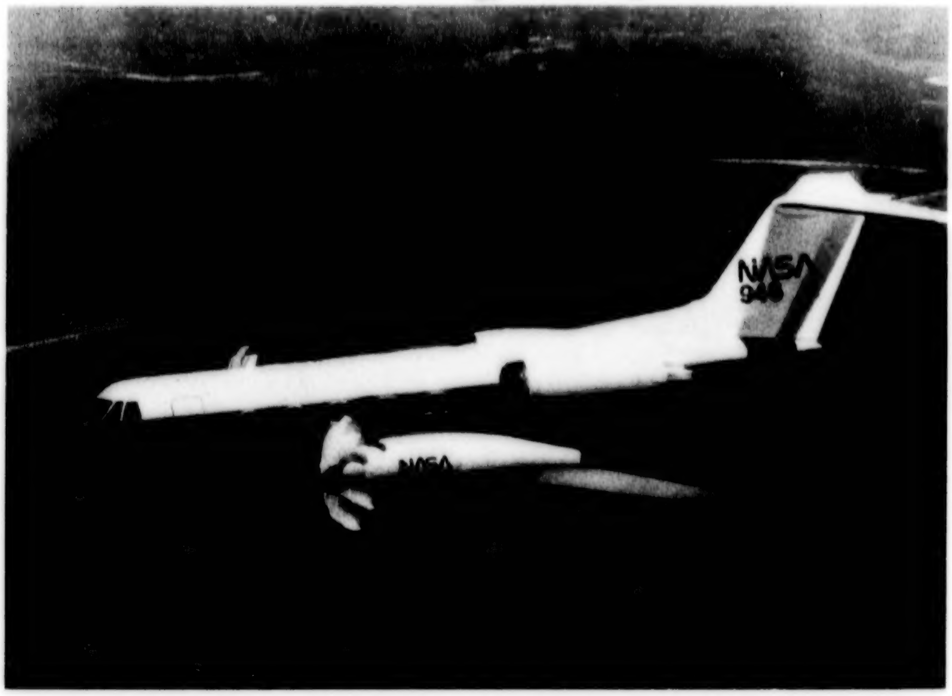


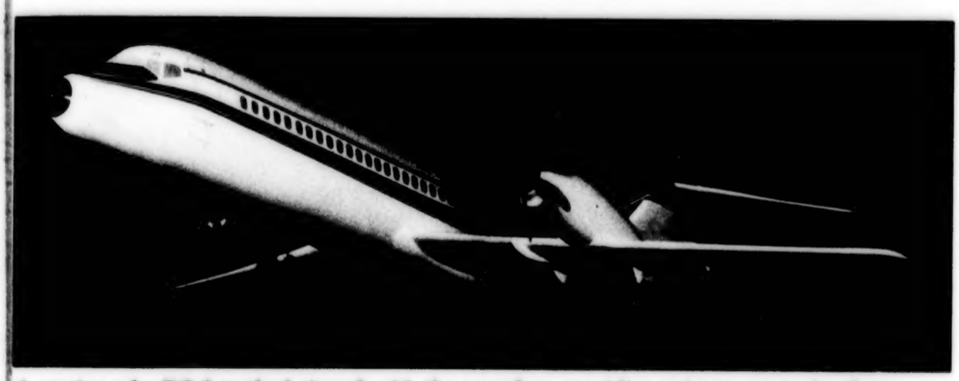
An artist's impression of a testbed Gulfstream II modified for large-scale propfan tests.

If initial flight tests are carried out beginning in 1987, inservice aircraft could be operational by 1994–95. ATP research has aimed at the 100–150-passenger class of transport, since the short-to-medium-range market consumes over 55 percent of the fuel burned by the airlines in the free world. This is just where the major fuel savings of the propfan can be realized rather than on long-range flights.

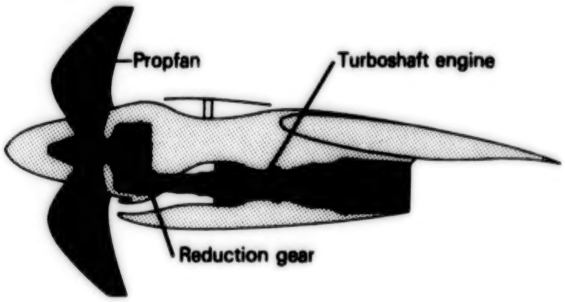
It is estimated that major portions of existing short-to-medium fleets will be replaced in the decade between 1988 and 1998. In the domestic fleet alone there are around 1200 Boeing 727s and 737s and McDonnell Douglas DC-9s that fit this replacement category. According to United Airlines, at least up to 1990, more than 50 percent of all airline industry departures will still be on segments with ranges up to 500 miles. More than 50 percent of total flight fuel worldwide is burned on trips of 1000 miles or less. Some carriers are already gearing up to seek proposals for new replacement airplanes in this size and range. If the propfan misses a significant portion of the 1988–1998 reequipment cycle, perhaps 10 or 15 years will pass before the next cycle affords the opportunity to fully realize its benefits.

If a production propfan propulsion system were available by 1990, it is estimated that 2000 propfan-powered aircraft of the 80–140-passenger size could be sold by the year 2000, saving as much as 20 billion gallons of fuel over their service lives.

A testbed DC-9 as it would appear for large-scale propfan tests.



A version of a DC-9 testbed aircraft with the propfans providing primary power in place of the normal turbofan engines.



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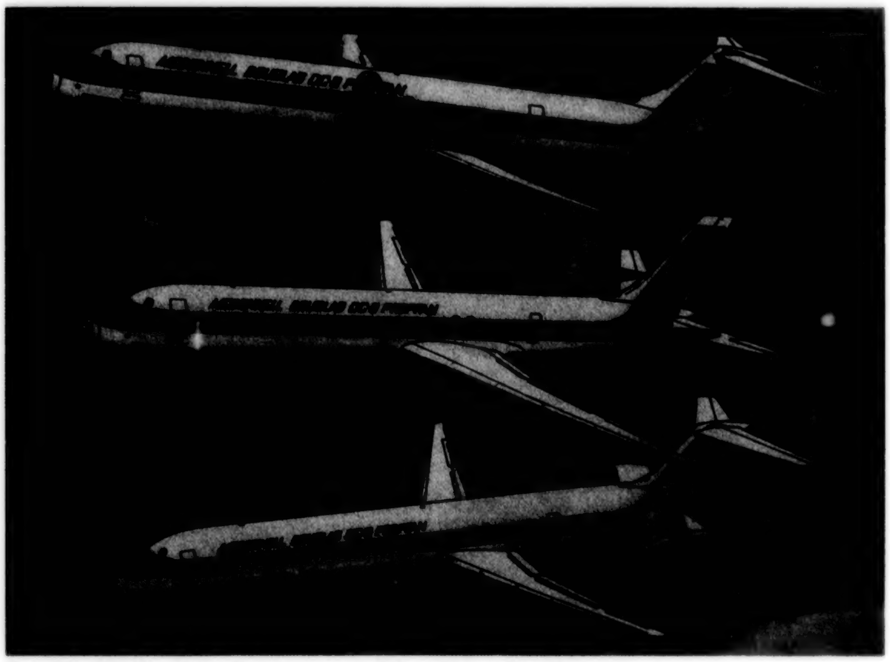
Douglas Aircraft has explored the possibility of a DC-9 with propfans mounted in place of the turbofans as primary power. If the technology can be proven, the company would aim for a 1990 delivery date of a new propfan-powered design, with 500 rolled out by 1995. To do this, Douglas would have to freeze the design by 1986, with a proven propulsion system to be available by 1990.

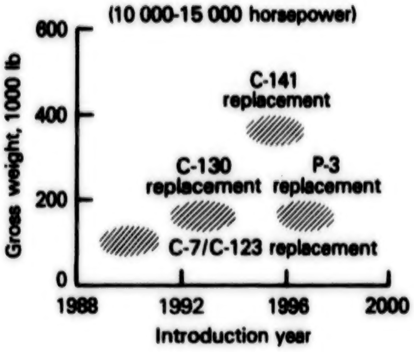
The aircraft engine companies have been taking a very hard look at what would be required for a production engine. Pratt & Whitney has estimated that it would require a $92 million technology verification program in addition to what the NASA ACEE/ATP program has been able to do. This propulsion system technology verification must take place before the engine companies would start a $1 billion development program for the above-mentioned market. The propfan has the biggest potential leap forward in fuel savings as far as new propulsion goes—but it also is the riskiest and most forward looking.

Engine companies are fully aware that the propfan could replace the turbofan in the transport of the future. But, will Hamilton Standard build a prop if there is no engine? Will Pratt & Whitney or General Electric build a power plant if there is no airframe? Will Douglas or Lockheed or Boeing build an airplane if there is no engine or prop?

Hamilton Standard has estimated that after the government has invested $200 million on the propfan, industry will need to commit another $1.8 billion to



Possible DC-9s of the future powered by advanced turboprops.



Military applications of the propfan have been suggested for the upcoming replacement cycles on several aircraft. The military services remain interested in the possibilities of the advanced turboprop.

develop and build the product. This is without many of the propfan research projects further in the future that are not being investigated: counterrotating props, pushers, remote engines with shafts, advanced blade shapes, and improved materials.

Even with the great potential fuel savings, the heart of the matter is worldwide competition to sell fuel-efficient aircraft. Foreign companies are forging ahead with new turboprop aircraft. There are government-sponsored projects abroad on propfans, and countries trying to accelerate research include France, England, Japan, and the U.S.S.R.

Among potential beneficiaries of the propfan are the U.S. military services. There are significant benefits in future military cargo, patrol, and long-range subsonic strategic aircraft, not only in fuel savings, but as performance gains in takeoff and landing runway requirements, range, loiter time, and enhanced payloads.

Naval Air Systems Command has expressed interest in turboprops in connection with future long-range, long-endurance missions, such as maritime patrol. It has termed the NASA ACEE/ATP program well planned and conceived and has expressed interest in continued NASA technology verification.

The Air Force Aeronautical Systems Division (AFASD) has noted that NASA verification and provision of a data base will be required before the Air Force can develop future propfan-powered aircraft, such as a C-130 replacement, a long-range heavy transport with unrefueled round-trip capacity, or a continuous patrol, long-endurance aircraft. As a result, AFASD has encouraged acceleration of ATP.

Chapter 5
Composite Structures

Since the first days of aircraft design, weight reduction has been of primary importance. Extra weight requires additional fuel to move an airframe from one point to another. In addition to the aforementioned specific fuel consumption and lift-to-drag ratio, payload/weight fraction or aircraft operating empty weight is a major factor in aircraft energy efficiency.

To keep airframes light, manufacturers began with wood, fabric, and wire, reserving metal for only the most essential components. The next major transition took the form of all-metal aircraft, primarily aluminum, and the industry found itself hard pressed to afford the cost of retooling. But it was done, and today the metal aircraft is universal.

Now a new family of construction materials made from fibers of graphite, glass, or man-made materials held in an epoxy matrix are being introduced into the aerospace industry. These composites are stronger, stiffer, lighter, and potentially less expensive to produce than conventional metal structures, but the transition can be costly.

NASA and several of the aircraft companies have been researching the use of composites for many years, but the major impetus came in the early 1970s. The initial spur was a meeting of industry, university, and government representatives in 1972. Their goal was to develop a long-range planning study for the eventual use of composite materials in both NASA and U.S. Air Force research projects.

Under the overall project designation of RECAST, the joint study cited two major stumbling blocks to increased usage of composite materials: lack of confidence in the materials and cost. There had been no large-scale applications to obtain realistic production cost data or service life information. Initial costs of introducing a new material are high because there is no volume production demanded by widespread application and there is no widespread application because the cost has been high. Some way must be found to break this cycle.

The joint study approached these two barriers with a series of recommendations. First, to build confidence, it suggested that some programs be established to fabricate and test composite components under realistic service conditions. Second, it encouraged the application of composites to new designs. Third, it

recommended a program of in-depth studies that would develop the technology and provide a data base for designers.

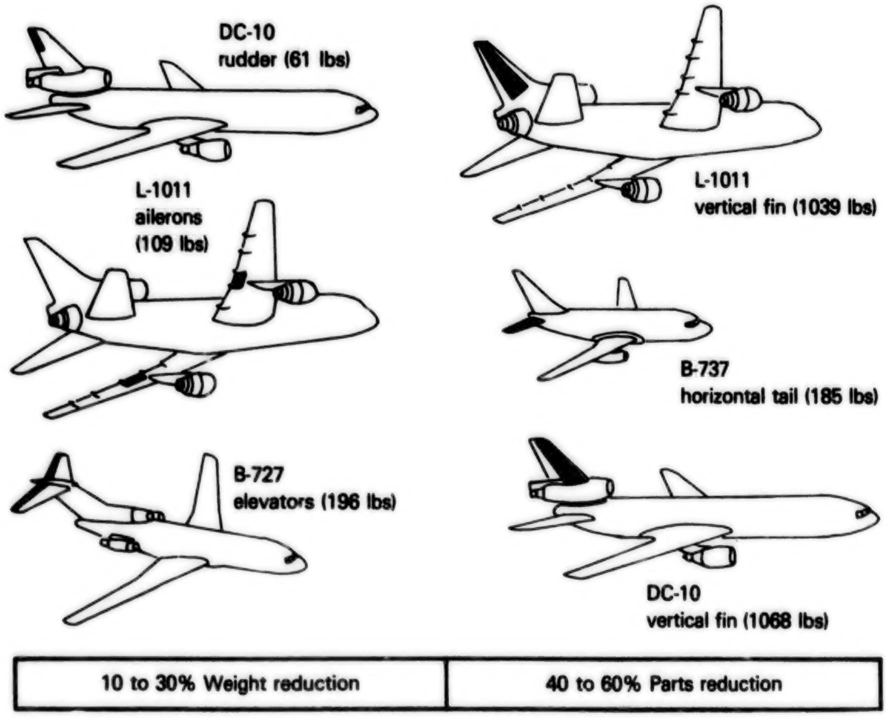
On the question of cost, the study acknowledged that it was closely related to volume but that improved structural concepts, improved design procedures, and innovations in materials and fabrication techniques should result in some major cost reductions.

NASA then included composites in the ATT as well as applications to existing vehicles such as spacecraft, power plants, and transport aircraft. Although aimed directly at one or more of these specific uses, the application of composite materials was expected to produce data that would be of a much more general nature for the widest variety of vehicles and engines.

By 1976 and the start of the ACEE program, composite research and application was one of the six major areas to be investigated through Boeing, Douglas, and Lockheed, coordinated by NASA Langley.

The ACEE Composite Primary Aircraft Structures program is pointing toward ever-increasing use of composite materials on transport aircraft—first on the small, secondary components in the early 1980s and then on increasingly complex larger-scale structures through the 1990s, when weight reductions can result in fuel savings of over 15 percent.

ACEE composite components already being flown, providing weight and parts reduction.



NASA's composites program is intended to provide commercial and military air transport manufacturers with both the technology and the confidence they need to commit themselves to producing composite structures. The leap from metal to filaments of graphite, glass, or Kevlar arranged in a matrix of epoxy, polyimide, or aluminum is a bold one.

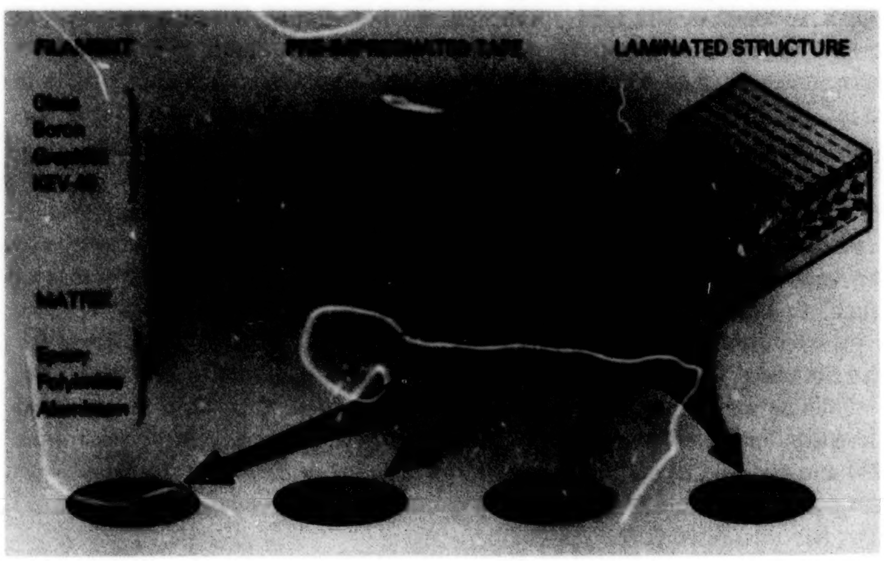
MANUFACTURE

The filament materials can develop very high strength, approaching that of single crystals of the material. By proper arrangement in a matrix, that strength can be concentrated along a line, in a unidirectional composite, or in random directions. The weight reduction comes from the strength-to-weight and stiffness-to-weight properties of the material. Potential cost reduction comes from the fewer number of pieces that make up a composite assembly, compared with conventional metal structures. A further cost saving results from the fewer number of fasteners required for assembly.

A typical design application of a composite material takes full advantage of its special characteristics. Contemporary graphite-epoxy composites available from commercial sources show ultimate strength and stiffness as high as steel but with one-fourth the weight. In addition, the fiber can be oriented in the desired direction to provide tailored stiffness properties.

Fabrication is simple, using a hand lay-up technique similar to that used in building a fiberglass boat hull or car body. The skill can be learned in a fraction

Composites are built up in layers of filament within a matrix, resulting in greater strength than metal. Note how filaments run at different angles in successive layers of matrix.



of the time it takes to acquire competence in sheet-metal fabrication. Automated cutting and lay-up techniques are around the corner.

PROPERTIES

One of the most important properties of composites is their resistance to corrosion, an enemy to any aircraft built of metal alloys. Possible sources of corrosion are everywhere; at fasteners, where they pierce successive layers of different metals, or inside the fuel tanks, where strains of bacteria thrive on metal spars. However, composites, although immune to corrosion, can contribute to galvanic corrosion in the presence of some metals.

There were delamination problems on some test articles, in which the layers of material begin to separate, but the companies worked out a manufacturing process to cure this malady.

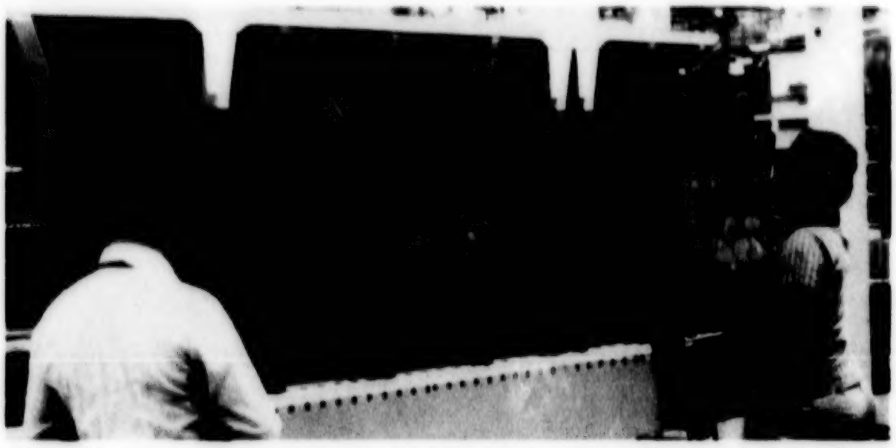
INDUSTRY

NASA's first step in the program to build industry confidence in composites was to plan for the development, fabrication, and testing of a number of components of aircraft secondary structures, those parts of an airframe that are lightly loaded and are not critical to the safety of flight should they fail; examples are access doors, fairings, and sections of multiple and redundant control surfaces.

Contracts were let for the design and fabrication of sets of wing spoilers for the Boeing 737, some external fairing panels for the Lockheed L-1011, and the upper segment of the split rudder on the McDonnell Douglas DC-10. The primary purpose of the study was not to save weight—that was a known fact with these materials. The real goal was to have some composite components in daily use in the active environment of a commercial airline, where rain and snow, ice and hail, and dust and dirt would add to the routine wear-and-tear on the pieces.

For the ACEE program, the NASA plan called for a phased development leading by steps to the design, fabrication, and test of a large-segment wing and fuselage typical of the type around which a future enegy-efficient transport might be built. The first phase of the program was a series of contracts for representative secondary structures: elevators for the Boeing 727, ailerons for the Lockheed L-1011, and rudders for the McDonnell Douglas DC-10.

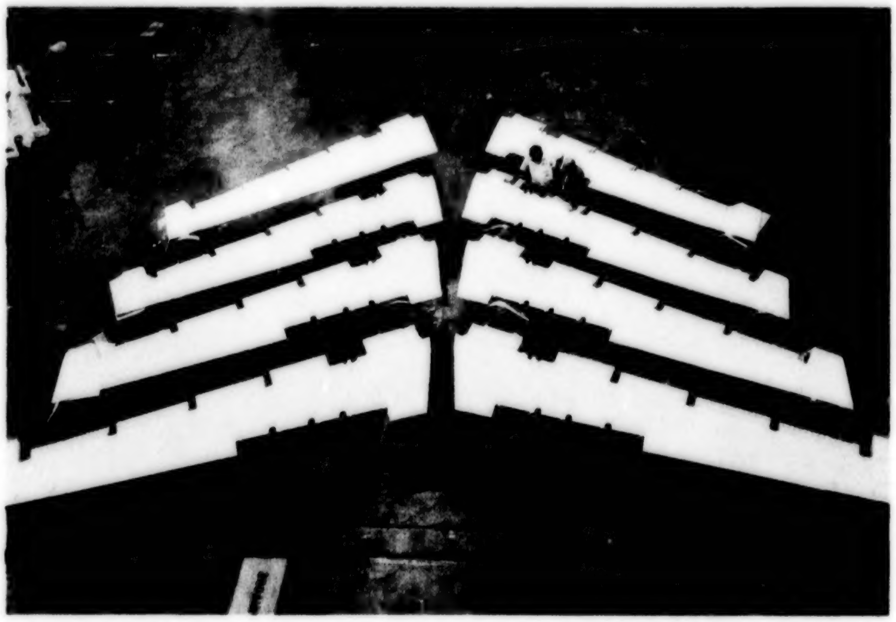
These were followed by contracts for medium-sized primary structures in the second phase of the program: the horizontal stabilizer structural box for the 737 and vertical fins for both the L-1011 and the DC-10. In the final phase—the development of the wing and the fuselage sections—everything learned from the first two phases would be applied.



A weight saving of 26 percent was achieved in the construction of this L-1011 aileron through the use of composites. Since the number of parts has been reduced, it is hoped that the manufacturing costs of composites can match those associated with conventional metal alloy structures. A thin sandwich cover skin, formed of graphite-epoxy tape and a syntactic core of epoxy, has such inherent stiffness that the number of bracing ribs was reduced from 18 to 10.

DC-10 upper aft rudders were among the first composite components built under the ACEE program for airline evaluation. A great deal of confidence has been gained as a result, nurturing industry interest.

The elevators on this United Air Lines Boeing 727 are made up of composite materials for service evaluation.



Four sets of composite elevators for the Boeing 727 before installation on United Air Lines aircraft for "real world" evaluation.

A Boeing 737 undergoing conversion to a composite horizontal tail.

The composite tailed 737 lifts off for the first time on September 26, 1980.

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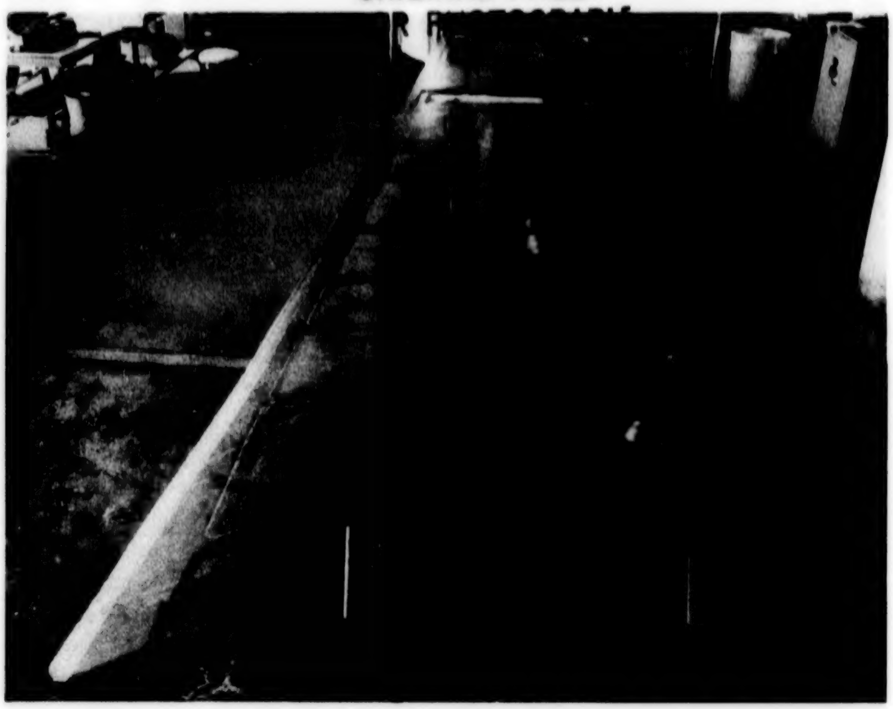
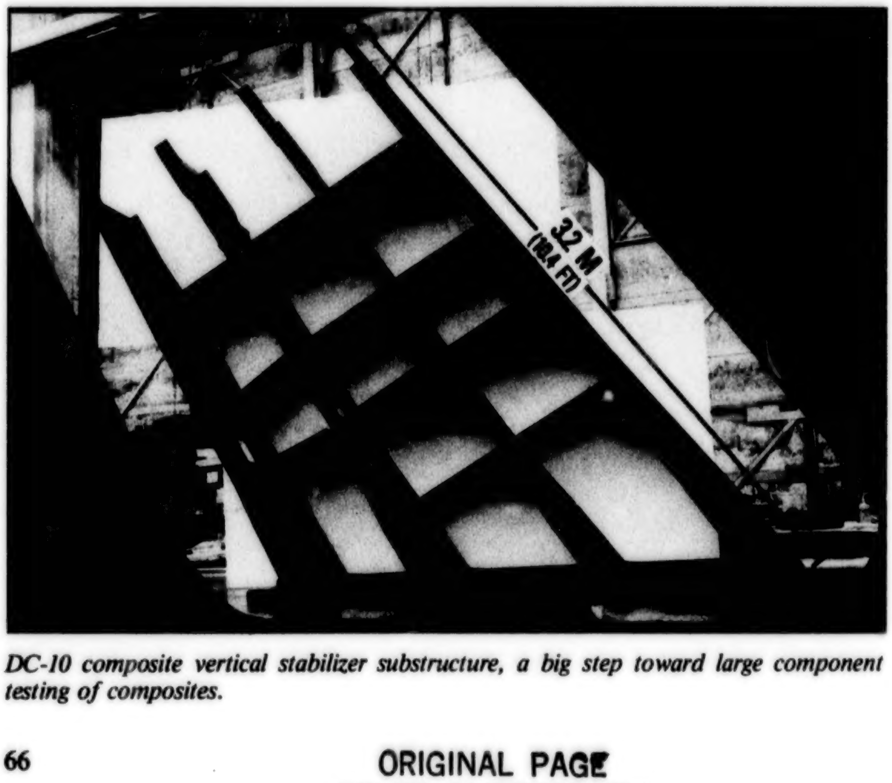


Graphite-epoxy cover for the DC-10 vertical stabilizer.



DC-10 composite vertical stabilizer substructure, a big step toward large component testing of composites.

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TESTING

Because composite components were to replace equivalent metal structures on passenger-carrying aircraft in airline service, each part had to be certified as meeting the requirements of the Federal Aviation Administration (FAA). The timetable called for all the first-phase components to be in airline service by 1981, and the first two medium-sized primary structure pieces were to be test flown the same year. Verification of all the test data and establishment of service life characteristics were scheduled to take up to 5 years.

The composite structures are being fabricated with production-quality tooling. In addition to the components built for in-service testing, at least one set of each part was constructed for ground testing. To meet FAA certification requirements, one example of each flight-worthy component must undergo ground vibration, in-flight flutter, and stability and control tests.

To obtain a sufficient quantity of each composite part to establish a learning curve so that valid estimates of manufacturing costs could be made, Lockheed built 6 sets of ailerons and 3 vertical fins for the L-1011, Boeing fabricated 5 complete sets of horizontal stabilizers for the 737 and 5 shipsets of elevators of the 727, and McDonnell Douglas set up 20 upper aft rudders and 3 vertical fins for the DC-10. The parts in airline service will be treated exactly like the metal components they replace, receiving the same periodic inspection and maintenance.

Since one of the most important factors governing the use of composites is manufacturing cost, the ACEE components have sacrificed some weight savings to achieve design simplicity and reduced parts count. The Boeing 727 composite elevator has skin panels of single-piece sandwich construction that require only simple tooling, and the number of interior ribs has been reduced from seven to two. The net result is a reduction of 40 percent in parts, 60 percent in fasteners, and 27 percent in weight, including a reduction in the mass balance requirements.

FAA certification of the DC-10 rudder was completed without any major problems, and the part has been cleared for inclusion on the production line. Twenty rudders have been built, some of which have been flying since 1976, and the breakeven point of graphite-epoxy and conventional production rudders is projected to occur between 50 and 70 units.

Douglas found that they were able to co-cure the titanium in the end structure of the composite vertical stabilizer. The stabilizer spars are constructed in one piece and then bonded along with the ribs into the structure. Testing of a stabilizer box component was done in an environmental chamber under all temperature, humidity and load conditions. A complete, full-scale stabilizer was static and fatigue tested to meet FAA certification requirements.

These components may seem relatively small when compared to the aircraft, but they are significant steps toward full-scale production. The DC-10 upper rudder segment is 12 feet long, saving about 30 percent in weight over the

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The small rust-colored area on the right wing trailing edge of this L-1011 is the composite inboard aileron. For inflight evaluation, ACEE program managers decided to install composite components on areas where failure would not endanger the flight.

metal surface it replaced. The L-1011 vertical fin measures about 9 by 25 feet, saving about 25 percent in weight, and the B-727 elevators use 14 versus 27 ribs, with the number of fasteners reduced by around 70 percent.

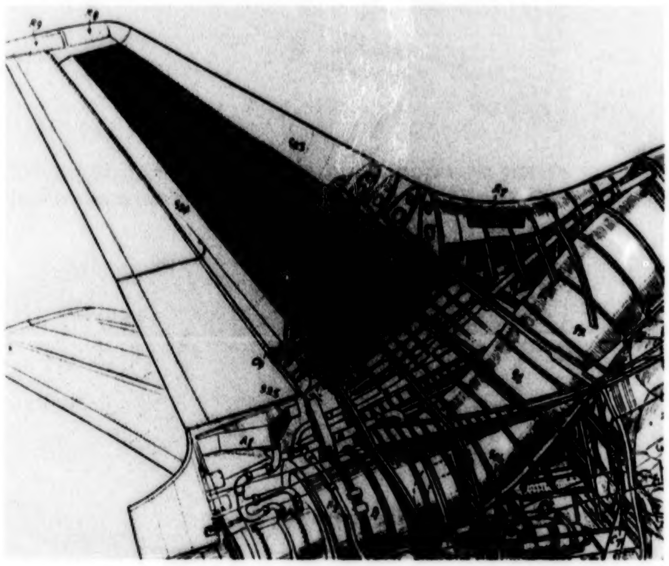
The aircraft companies did not come this far without some experience in how to handle composites. All had started to work with composites before NASA offered the ACEE program. Lockheed developed Kevlar components for the L-1011, primarily as fairings and fuselage to wing fillets, and then tested them. With the −500 model, all fiberglass was replaced with Kevlar, and 2200 pounds of the composite per aircraft were installed. NASA had set the tone with its own research, leading to early application.

In working on the L-1011 fin, Lockheed devised a single-stage process whereby all the graphite was layed-up in around 12 days. Prior to this, it took much longer to perform the graphite work and the fabrication costs of the 30 percent lighter product were the same as those for aluminum. Reeducation of Lockheed's engineers was required in leaving aluminum construction techniques for different composite construction techniques. There was an order of magnitude step down in complexity due to the lack of need for reinforcement in the middle of the fin ribs.

There were fears about drilling holes in graphite due to the breakout tendency similar to plywood on the opposite side, but a simple masonite sandwich solved that problem.

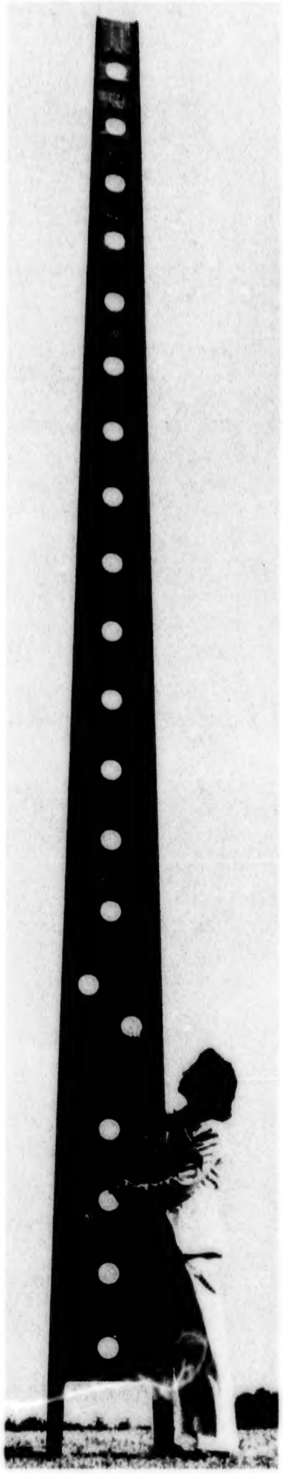
When Boeing started design work on the 7X7 (now the 767) in 1971, it was to have been an all-aluminum aircraft, but NASA's timing was significant.

The 25-foot high graphite epoxy L-1011 vertical fin nears completion at Lockheed. It reduced weight 25 percent.



Portion replaced in the L-1011 tail by the composite structure.

Composite section's location is outlined.



This 25-foot Lockheed L-1011 TriStar fin spar, made of graphite-epoxy, weighs only 40 pounds, a 50 percent weight saving. Three spar and box assemblies were made for testing on L-1011s.

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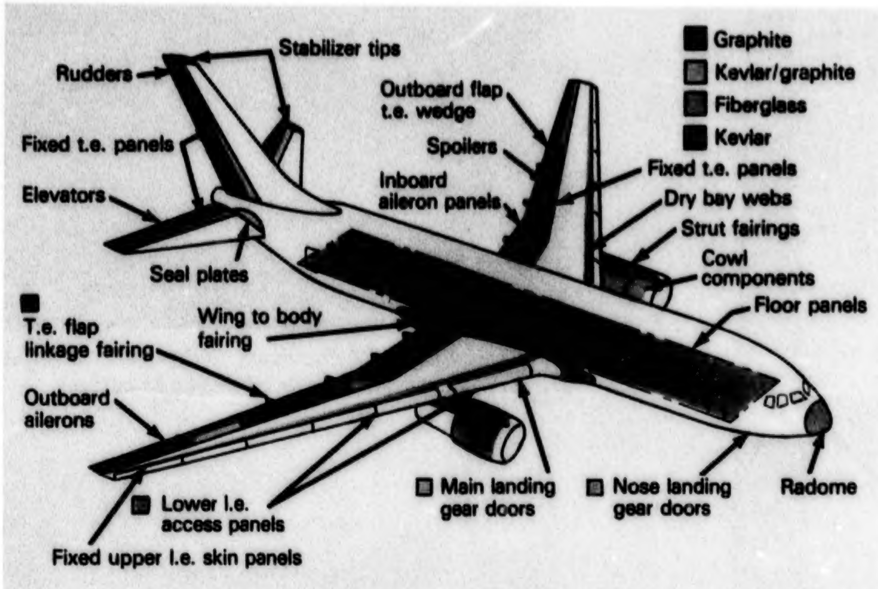
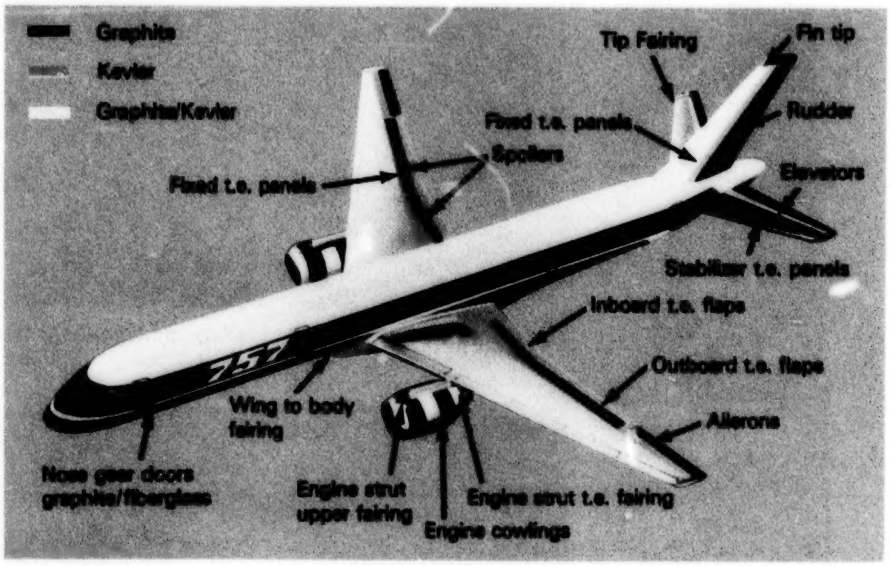


Boeing has made a major leap into the use of composites on its next airliners, the 767 and 757. These diagrams point out just how much of each aircraft is devoted to the new construction technique.



Given the incentives to do composites research, Boeing decided to incorporate as much graphite as possible into the new transport. After good results on in-house use of fiberglass in an epoxy matrix on the 737 and 747 in the early 1960s, Boeing tested graphite on the Boeing/NASA 737 spoilers and joined the ACEE project.

While risks were still formidable on a large composite commitment for the 767, even though no primary structure was involved, Boeing pressed on through several problems and selected Kevlar/graphite hybrid materials, along with graphite, Kevlar, and fiberglass, for extensive use on the aircraft. The weight saving for the 767 came to 2028 pounds, putting composites squarely into the center of aircraft construction.

MAJOR USE

The next ACEE composites program centers around composite wing studies by Boeing, Douglas, and Lockheed. Each contractor has assessed the present state of composites development as it relates to wing design and is under contract to address long-lead key technology issues. Boeing is studying durability and damage tolerance of primary wing structure; Lockheed, fuel containment and damage tolerance in large composite primary structures; and Douglas, critical joints in advanced composite wing structure. These studies should pave the way for an all-encompassing wing technology development program.

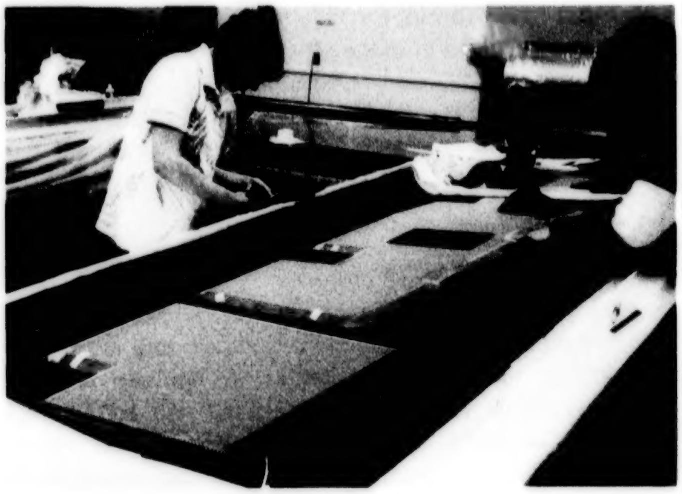
Ever since the ACEE program has existed, manufacturers have been encouraged by the leap forward they have been able to make in composites. They have moved from what were expensive, exotic materials to routine manufacture by workers inexperienced in composite structures. ACEE has allowed identification of gross inadequacies in material specifications that grew out of the plastic industry. Primary structure must be approached far differently than the nonstructural plastics of the previous 20 to 30 years.

With recent emphasis on high aspect ratio wings for future transport design, composites have been found to permit the higher aspect ratios, but structural problems have surfaced as the price for high aerodynamic efficiency. The problems revolve around the aeroelastic characteristics of such a wing. Because of its large span, relatively narrow chord, and the sweepback angle, the wing is inherently susceptible to air loads that could, without corrective action, make it respond erratically, perhaps dangerously, in flight.

Active controls offer one way of easing the problem (see chapter 6) but passive control methods, using a new approach to the structural design of the wing, also offer great promise. The passive method is based on an aeroelastic tailoring of the wing, designing and fabricating the needed stiffness in critical areas to produce the required dynamic response where desired. This is a far easier procedure to achieve with a composite structure than with a metal one.

NASA has begun a program that will design, fabricate, and test a wing with aeroelastic tailoring in wind tunnels and on a drone aircraft.

Composites are also contributing to the evolution of a laminar flow control (LFC) system for advanced transports with excellent surface smoothness and lack of distortion or waviness (see chapter 7). Part of the LFC study is concerned with new kinds of structural designs needed to make the laminar flow system a reality. The structural requirements for a typical LFC wing, as currently visualized, call for a very efficient, light, and stiff structure capable of providing a



Composite work at Boeing took a major thrust with the 767 and 757 programs. The ACEE program did a great deal to encourage Boeing's leap into this area, which will be just as significant as the change from wood and fabric to aluminum. Photos show Boeing employees and some of the new materials and techniques of manufacture. The simplicity of fabrication is often significant as are some changeover costs.

Boeing's new 767 on rollout at Seattle.

large internal volume for the removal and handling of the boundary layer air. Composites are obvious candidate materials for such a wing design and in fact are being considered for that purpose.

A glove structure was conceived as one way of modifying an existing wing for early tests of a representative LFC section. The glove included an inner structure built of blade-stiffened composites. The blades provided a set of boundaries for the internal ducting used to handle the boundary layer air.

Another example visualized a slotted titanium surface bonded to a stiffened composite structure to carry the primary loads imposed on the wing. Stiffeners in the composite piece form the side walls of the air ducting.

ACEE has been a boon to the aerospace industry. Technology transfer between government and industry and within industry itself has pushed the companies 5 to 10 years ahead in composite research and utilization. Hands-on experience has demolished the fear factor surrounding the new materials, which have entered the real world of transport aviation. The large body of data gathered now has the confidence of the FAA and the airlines, something that would not have been possible, at least this soon, without the NASA ACEE program.

Using more composites than any previous aircraft except the Lear Fan, the Boeing 767 is seen here in flight over the state of Washington. Much of the technology proven in the ACEE program is flying in this aircraft.

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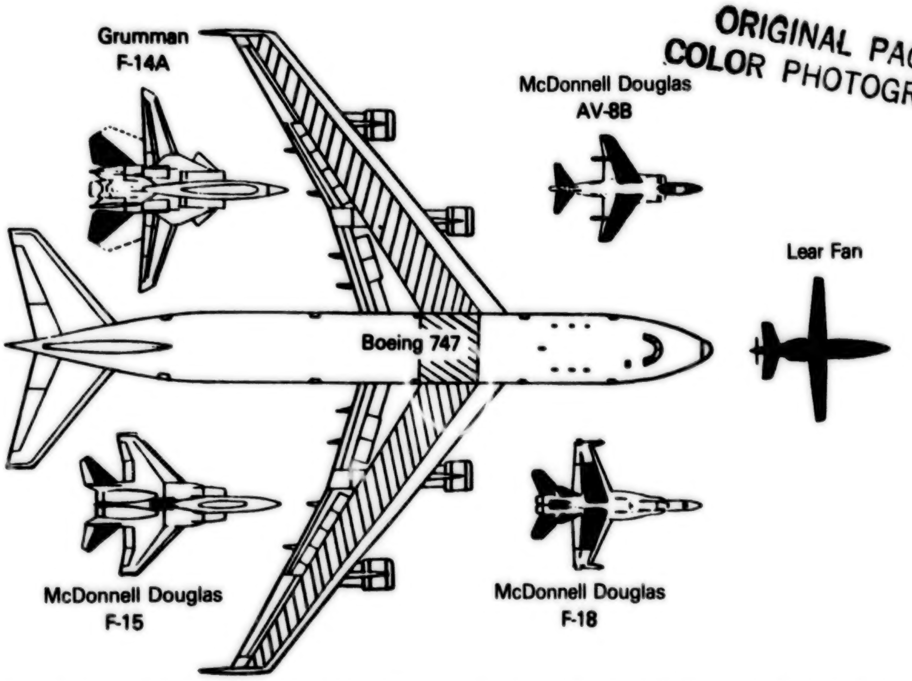

Large primary structure composite development is the next major challenge in this area of research. Diagram gives some idea of aircraft flying with major composite portions in their airframe compared to a desired application to the Boeing 747. The Lear Fan is currently flying as an all-composite aircraft.

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Chapter 6
The Energy Efficient Transport

The challenge of advancing aircraft design has been a continual process in man's mastery of the air. Engineers have had to face a steady parade of trade-offs in designing aircraft, primarily in the effort to have lift overcome drag with ever-increasing efficiency.

The NASA ACEE program has been focusing technology development on aerodynamics and active controls to form a data base for manufacturers that would assist them in building energy-efficient aircraft. Although this part of ACEE has been called the Energy Efficient Transport (EET) program, there is no single aircraft being developed for flight testing. Rather, several areas are being researched simultaneously.

Aerodynamics addresses the effects of an aircraft's detailed geometry on airflow over its entire surface and the forces on and motions of the aircraft that result from this airflow. Active controls are flight control systems in which aircraft control surfaces are linked to a computer and sensors, automatically and immediately reacting to limit any unwanted motion or aerodynamic loads on the aircraft structure while providing augmented stability. Future systems will have comparatively lightweight electrical wiring to replace the heavier rods, hinges, and hydraulic lines that normally transfer the pilot's commands from the cockpit controls to wing and tail surfaces. Active controls also permit reductions in size and weight of the wing and tail. The substantial reductions in weight, trim drag, and skin-fraction drag that result contribute to increased fuel efficiency.

A hypothetical EET would combine a number of technological advances in several aeronautical disciplines. The plane would feature a supercritical wing of high aspect ratio, with winglets at its tips and high-lift devices on its leading and trailing edges; a system of active controls to moderate maneuver and gust loadings; and a meticulous integration of the airframe and propulsion system.

AIRFOILS

The supercritical wing, a NASA development dating back to the mid-1960s, uses an unconventional airfoil shape to control the flow, delaying a sudden increase in drag (due to more uniform pressure distribution) until the aircraft reaches higher Mach numbers. As an aircraft approaches the speed of sound, Mach 1, airflows that are curved above the surface of a wing accelerate to a

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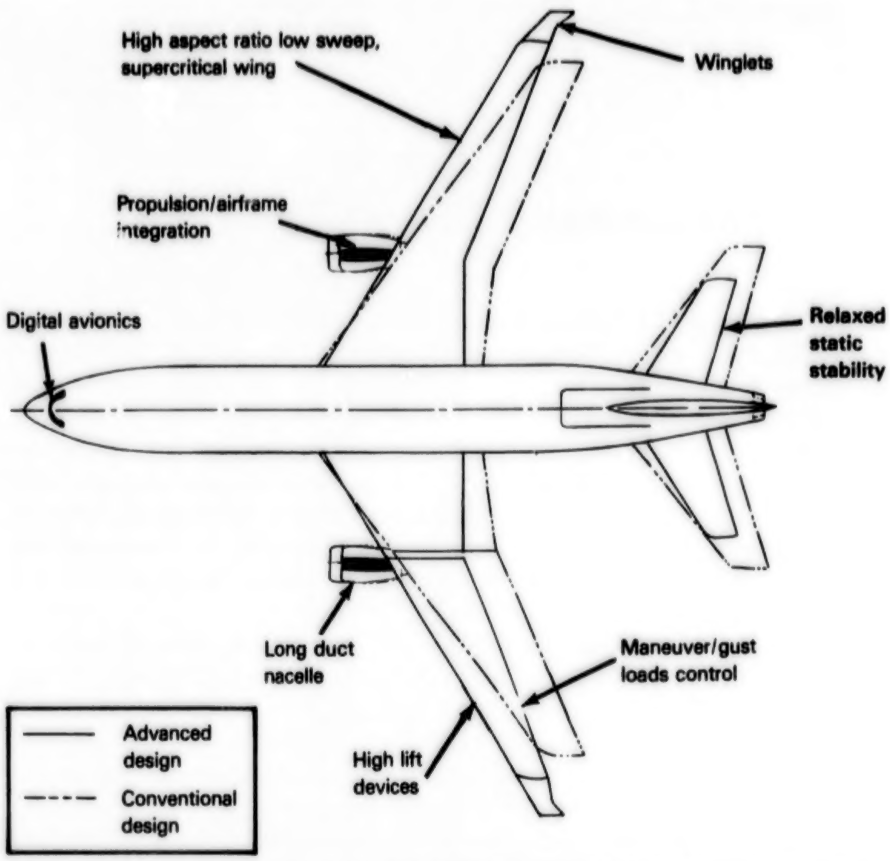
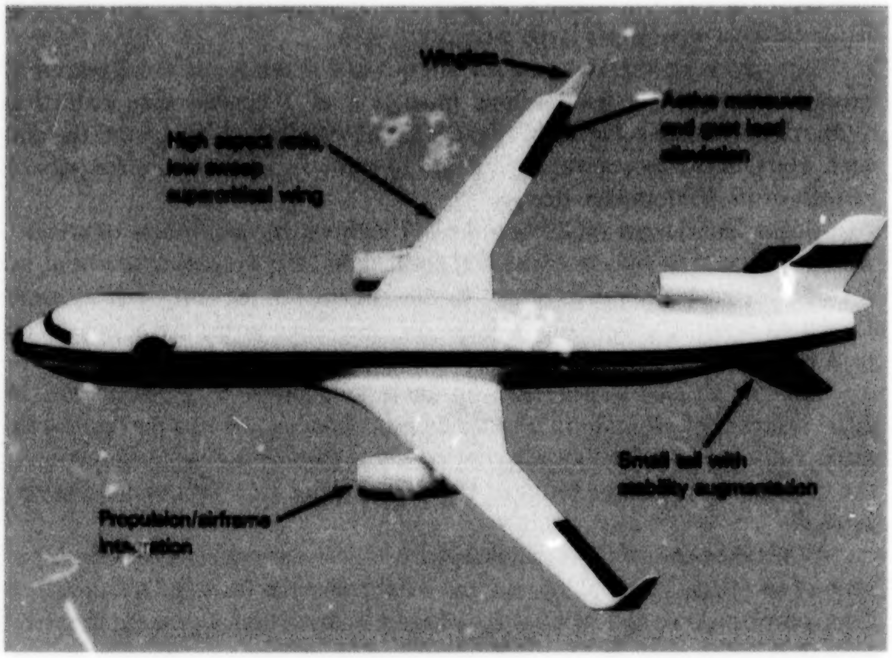


The Energy Efficient Transport portion of ACEE investigated these advanced technology features to be applied to future transports. It was not a program to produce an actual airframe design.

critical speed at which a shock wave forms, upsetting the smooth flow and causing a sudden, dramatic drag increase. That shock wave is like what was called the "sound barrier" years ago, a theoretical hindrance to high-speed flight. The barrier was conquered with brute thrust, but the trick now is to subdue it quietly and efficiently.

Indications are that application of supercritical aerodynamics to a new wing design for aircraft similar to contemporary wide-body jets would reduce the fuel burned for a given trip by 10 to 15 percent by permitting a thicker wing section with an increased wing aspect ratio (longer span versus width), which decreases induced drag. This thicker wing can be incorporated without incurring any additional drag penalty, while providing more useful internal fuel storage and greater depth for a lighter wing structure.



An EET of the future could look something like this after applying research findings. It features a supercritical wing with a high aspect ratio and low sweep, high-lift devices, winglets, and maneuver/gust load control. The propulsion system is integrated carefully into the airframe, using the long-duct nacelle concept. Relaxed static stability and digital avionics systems are part of the active controls. Composites also are utilized.

WINGLETS

Winglets, which look like small jib sails mounted at the wingtips, resulted from some of the same considerations of drag reduction that sparked development of the NASA supercritical wing. A major source of induced drag on a wing is the trailing vortex, a twisting, small-scale whirlwind that trails from wingtips with enough energy, in some cases, to upset following aircraft.

The difference in pressure above and below an airfoil creates a spanwise flow, which causes a vortex to form behind each wingtip with a great deal of associated drag.

A winglet, carefully designed as a lifting surface, is positioned to reduce the trailing vortex strength, subtracting drag and improving the ratio of lift to drag. Depending on the configuration and, in particular, the span load distribution on the wing, winglets can improve the lift to drag ratio by up to 8 percent.

Early wind tunnel tests were done on models of the Boeing KC-135, Douglas DC-10, Lockheed L-1011, and on a high aspect ratio supercritical wing.

The best results were obtained with the KC-135, which has a wing with less bending movement than most large aircraft.

Winglets were installed on a test aircraft and flown for almost 2 years with excellent results. The wind tunnel prediction of 7 percent drag reduction, although not totally achieved in flight, was sufficiently high to validate the concept. The U.S. Air Force was encouraged to make use of the results for possible retrofit of its Stratotanker fleet.

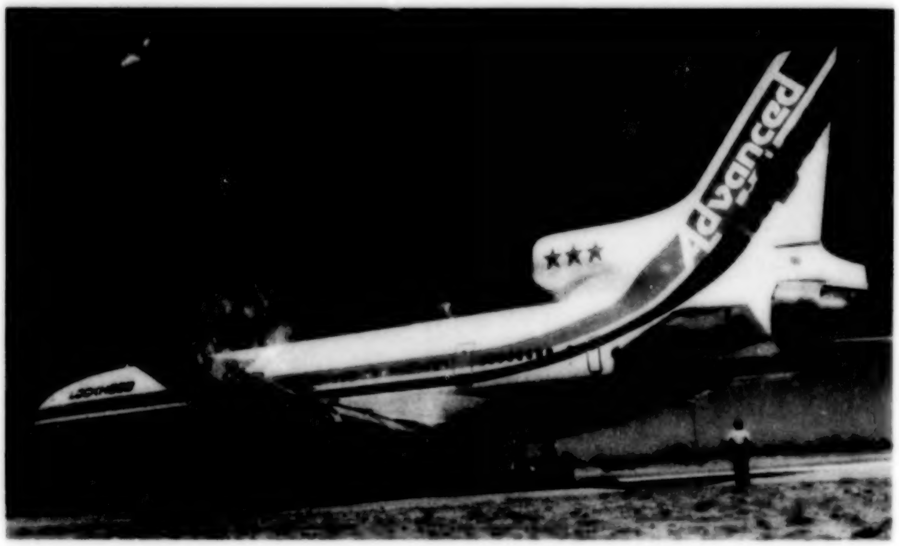
Boeing considered modifying the 747 with wingtip extensions or winglets with active controls but, in mid-1979, decided that the winglet alone would not provide adequate economic return to the airlines for the cost of fabrication. Lockheed opted to extend the wingtips on the L-1011 by the use of active controls instead of winglets.

Douglas decided to proceed with the installation of winglets on a DC-10. After a flight test program that lasted 2 years, Douglas solved a buffet problem through the use of a leading-edge device and is considering the introduction of the winglet on production aircraft. Retrofit of active DC-10s also is being considered.

Wingtip extensions, like winglets, serve to increase span and thus the aspect ratio of the wing. To avoid the cost and weight penalties for structural modification, active controls can be used for wing load alleviation. Lockheed elected to specialize in this area on their Advanced L-1011 TriStar.

A NASA/U. S. Air Force KC-135A winglet program used winglets about 12 feet high, with a 6-foot base chord and a 2-foot tip chord. They improved fuel efficiency by around 7 percent during cruise and could have provided the U. S. Air Force with a significant fuel savings; however, retrofitting the entire KC-135 fleet was judged too expensive.

Winglets are currently flying on the DC-10, as shown in this Douglas Aircraft photo.



The Advanced TriStar (L-1011-500), now certified for the marketplace, is a worthwhile result of the ACEE program; it is already saving fuel in everyday use.

AIRFRAMES AND ENGINES

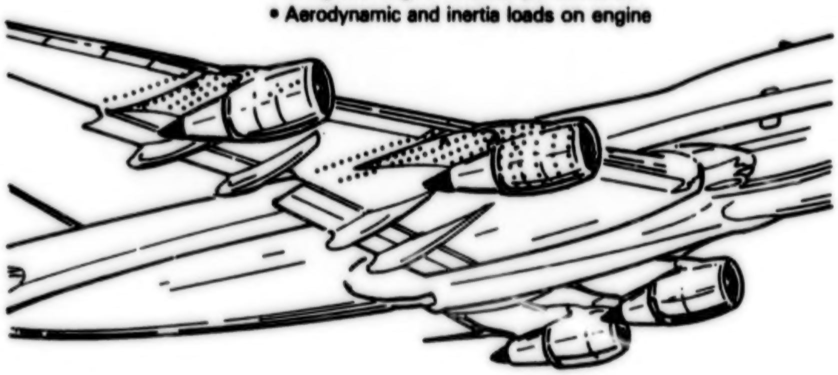
Another very important aerodynamic area for investigation is airframe/propulsion integration. Douglas investigated a mixed-flow long-duct engine nacelle for the DC-10, which was a product of its research in the NASA ATT program. Although the project never entered the hardware stage, enough

research was done by 1979 to determine that installation was achievable with little or no interference drag, which could have resulted in a 4.5 percent fuel savings. Flight test work on actual installation remains to be done.

A data base is required to validate analytical methods currently being developed for the investigation of airframe/propulsion integration. In 1979 Boeing undertook for NASA an ambitious installed propulsion system aerodynamics (IPSA) flight test program to measure 557 surface pressures on the inboard and outboard propulsion system installation of the no. 1 Boeing 747. This work was coordinated with the flight loads test on the same airplane to determine nacelle aerodynamic and inertial loads on engine installations that measured an additional 297 pressures on the same nacelles. These two tests formed the Nacelle Aerodynamic and Inertial Loads (NAIL) program. The combined data of these two programs have provided the most comprehensive data base in existence today on the physics of the flow about a propulsion system pylon mounted on the wing of a commercial airliner.

A joint NAIL program between Boeing and Pratt & Whitney was directed by NASA Langley and NASA Lewis. The concurrent flight loads test on the 747 with JT9D-7 engines was very successful in obtaining data on propulsion system aerodynamic and inertial loads in flight. The results revealed the highest airloads at low speed, high angle of attack, and high engine airflow—takeoff, for example. Inboard and outboard nacelle airloads were essentially identical; inertial

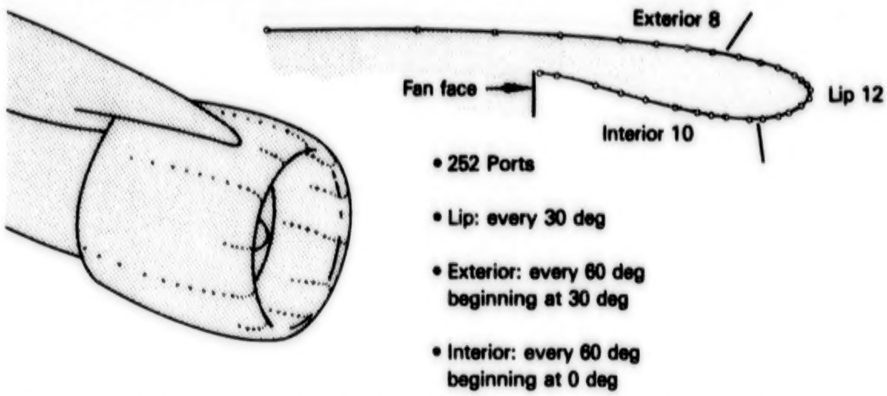
Objectives: in-flight measured data base
- Wing and engine installed performance
- Aerodynamic and inertia loads on engine



Joint program
- NASA - Lewis and P&WA
- NASA - Langley and BCAC

Instrumentation
- 693 Pressure measurements
- 30 Accelerometers
- 12 Blade clearance measurements
- 7 Rate gyros

The NAIL program was included in both the EET and ECI portions of ACEE. The aerodynamic objectives were to improve wing and engine installed performance through measuring deficiencies in nacelle and pylon design.



This diagram gives some idea of how the engines were tapped with pressure sensors—in this case, the inboard engine.

loads were lower than anticipated. The data will lead to more energy-efficient engines and installations.

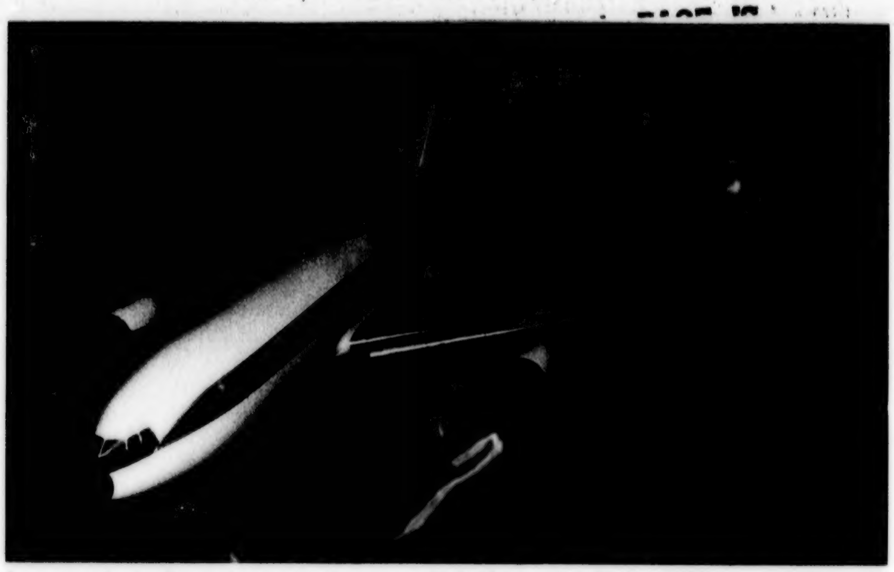
HIGH LIFT

High-lift devices offer yet another way of saving incremental fuel during two phases of flight: takeoff/climb and approach/descent. Contemporary transports extend wing flaps, sometimes coupled with leading-edge lift systems, to increase the available lift coefficient for takeoff and landing. Their extension also causes an increase in drag.

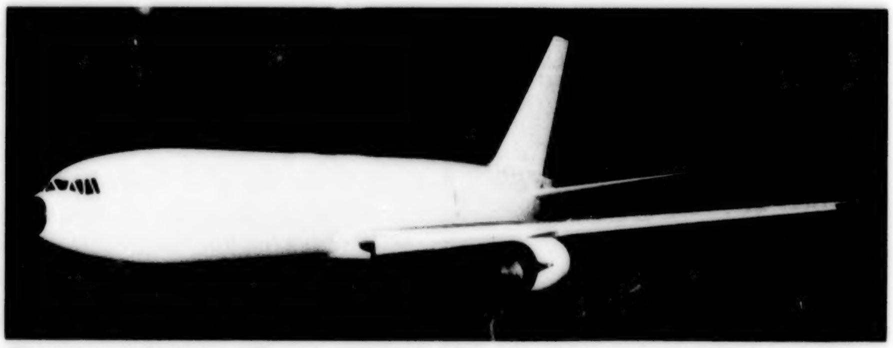
Typically, an air transport making a descent for a landing will extend flaps partially at first, then once or perhaps twice again before finally touching down with the flaps fully extended. Each of those flap increments is matched by an increase in power to balance the added drag. That power is used at low altitudes at which jet engines burn the most fuel and make the most noise as far as the community is concerned. Any way to reduce thrust as these lower altitudes is worth consideration.

NASA has studied a wide variety of high-lift systems, both passive and active, but now the effort is directed toward applying them to the leading and trailing edges of a supercritical wing. One such experiment combined leading-edge slats with a partial-span, two-segment slotted flap. For takeoff, a hypothetical jet transport built around a supercritical wing and high-lift systems of this type could generate a lift coefficient of about 2.3. Current wide-bodied transports with conventional wing designs generate takeoff lift coefficients between 1.7 and 2.2 at best.

Boeing and Douglas put a great deal of effort into analytical studies and wind tunnel tests for advanced high-lift systems, but they had to deal with wind tunnels that were not able to reach required design parameters. Boeing was able to develop high-lift designs that not only were more efficient (up to a 13 percent



Low-speed aerodynamics received a great deal of attention in the EET program through both computer studies and wind tunnel tests. This subscale model, tested in a Langley wind tunnel, has movable leading and trailing edge surfaces and control surfaces.



The same model being "flown" with the leading edge slats extended. The large, yellow-striped umbilical allowed the model to be controlled from a booth outside the tunnel.

Here the partial span two-segmented flaps have been lowered for testing. Leading edge slats also are extended.

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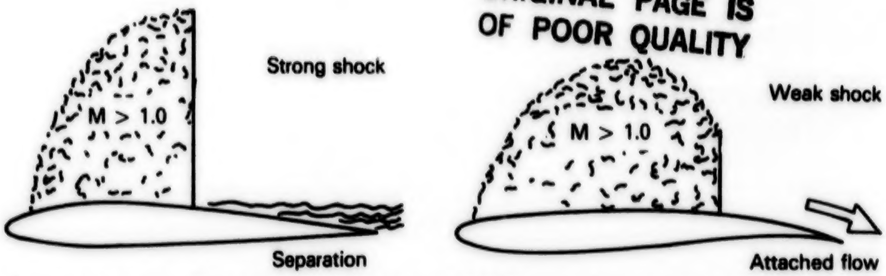


Supercritical wing flow phenomena (right) and difference from normal airfoils (left). At Mach 1.0 the shock wave moves further back along the supercritical wing. The flow remains attached instead of separating from the wing, increasing efficiency.

increase in lift coefficient) but required fewer lift devices on the wing, making it simpler to build and maintain. Results of this work were applied to new transports: the 757 and 767.

When Douglas made similar wind tunnel tests on an advance wing with a high-lift system, it obtained a very encouraging lift coefficient of 3.25. These results have been incorporated into the DC-X-200, a potential shortened fuselage twin-engine derivative of the DC-10.

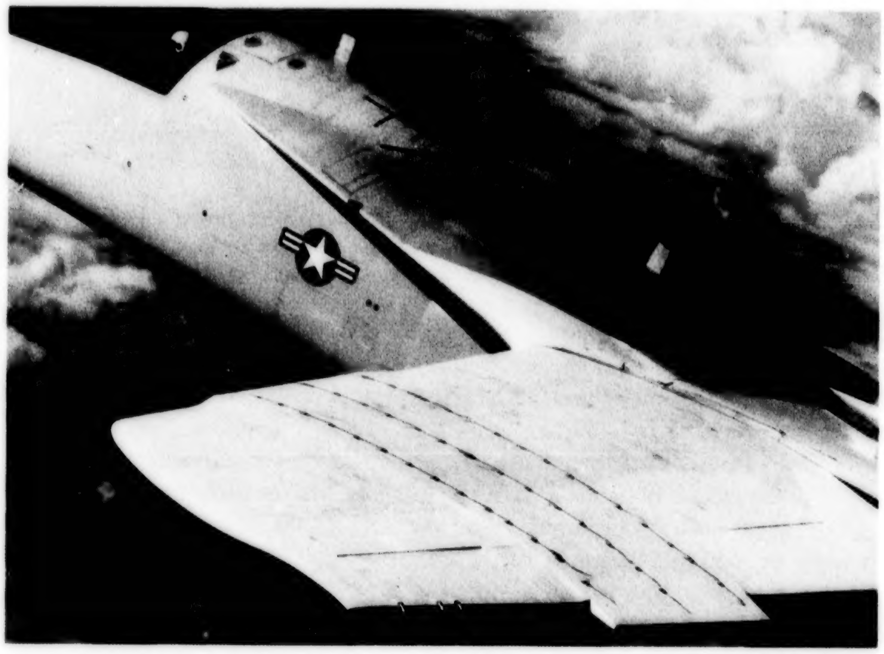
LAMINAR FLOW

Laminar flow on selected airfoils has also been a major area of study within NASA. It has been integrated into the ACEE program in three different areas of investigation: natural laminar flow, laminar flow control, and hybrid laminar flow (see chapter 7). Natural laminar flow was investigated as part of the EET program.

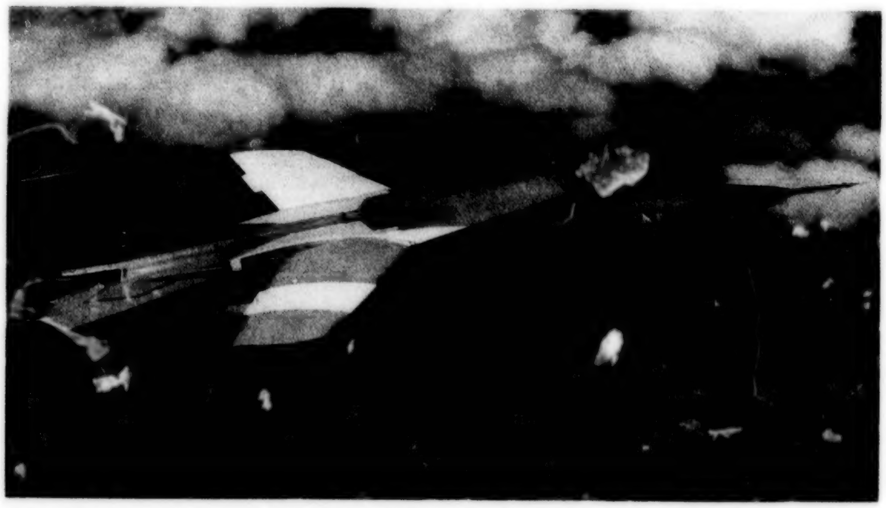
When the smooth boundary layer on an airfoil becomes turbulent, smooth laminar flow is lost along with aerodynamic efficiency. Laminar flow can be achieved through design with favorable pressure gradients over part of the wing. Adverse cross-flow effects induced by a highly swept wing leading edge, necessary for cruise at high subsonic speeds, limits the extent of laminar flow attainable. However, improvements may be possible with wing sweep angles up to or even beyond 23 degrees.

To demonstrate the possibilities, NASA completed a flight test program with a natural laminar flow supercritical airfoil incorporated in partial gloves on the wings of the Transonic Aircraft Technology (TACT) F-111. NASA redesigned the TACT airfoils, which were reworked at Boeing. The variable wing sweep feature of the aircraft permitted investigation of a number of sweep angles up to 26 degrees during flight at Mach .8 to .85.

A significant amount of natural laminar flow was achieved. At Mach .85 and 20 degrees of sweep, there was 50 percent natural laminar flow on both sides of the wing. Leading-edge disturbances in the airflow remained the major problem to overcome.



Natural laminar flow was investigated in flight on wing of the TACT program's F-111. The plane, which already had a supercritical wing, was fitted with a "glove" coated with plastic to form a supersmooth surface to reduce friction between the air and the wing's surface.



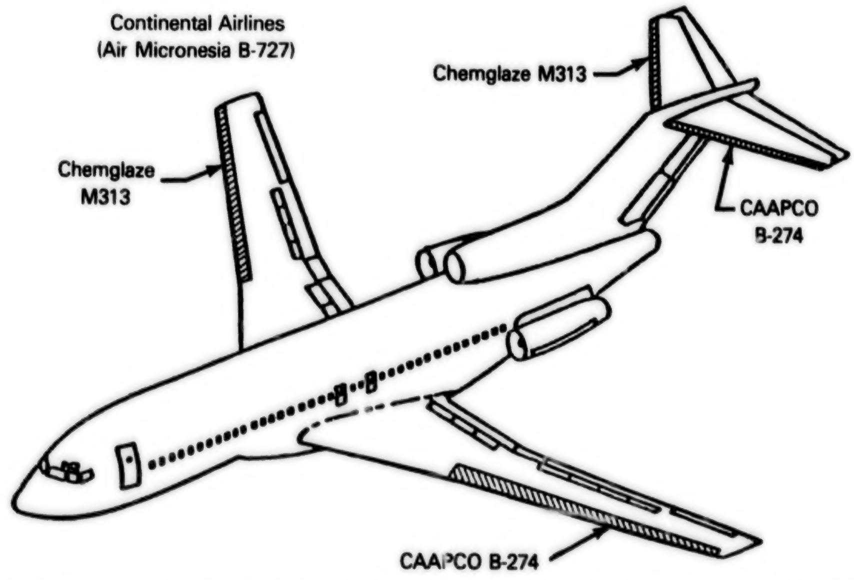
This photo shows the NLF F-111 in flight with the coated glove across the wing. It was found that natural laminar flow was maintained even when the wing was swept beyond test parameters and speeds. This very promising portion of ACEE research was scheduled for further investigation.

SURFACE COATINGS

One of the simpler drag reduction programs in EET came from coating aircraft similar to the Apollo spacecraft with Kapton, a film polyimide like the browning bags used to roast turkeys. Reduction in drag would come from improving or maintaining smooth external surfaces, with an important side benefit of reduced maintenance from the protection offered by the coatings.

In a NASA program conducted by Boeing, the large number of available materials was narrowed to 15 liquid coatings and 17 films used in various combinations with 13 adhesives. Elastomeric polyurethanes emerged from 17 screening tests as the best potential candidates. Films were found to have superior smoothness but were not durable in a rain impact field; thus, the remainder of the surface coatings program gave priority to liquid spray-on-coatings.

Two coatings, CAAPCO B-274 and Chemglaze M313, were selected for further investigation, with Astrocoat Type 1 (used on radomes) included as a reference material. Rain erosion, icing, hydraulic fluid exposure, lightning/precipitation static, and corrosion tests were conducted before the coatings were applied to wing and tail leading edges on a Continental Airlines (Air Micronesia) Boeing 727. The first flight evaluation was conducted in a high-rainfall (average 90 inches per year) environment, resulting in extensive degradation of the coatings. However, they were tested on airline transports for 6



Aircraft surface coatings were also investigated during airline evaluations. The coatings were found to inhibit erosion of frontal surfaces and to promote smoother airflow; however, maintenance costs were judged to be too high, and further investigation was needed.

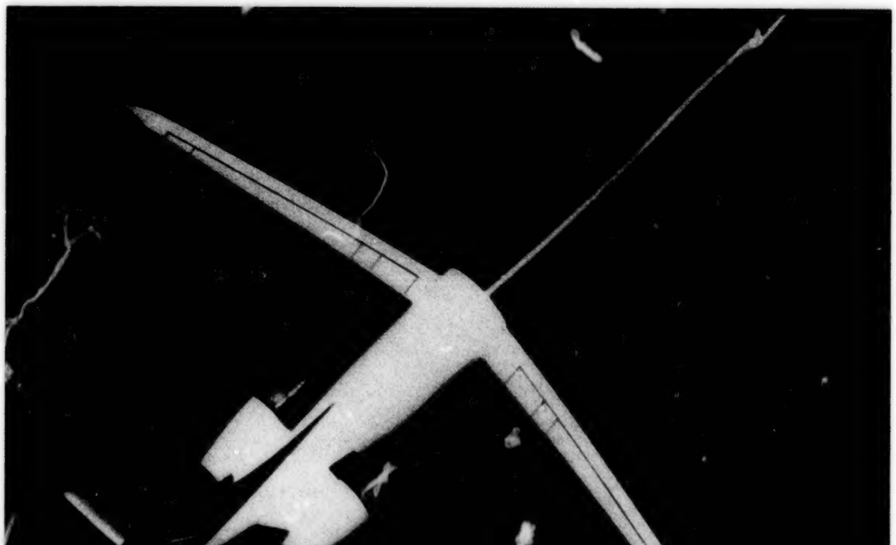
months after being applied before deterioration started, whereas a laboratory-coated control leading edge was in good condition after 4,800 flight hours. A Delta Air Lines 727 flew the coatings in domestic service, with excellent results on some of the parts and little evidence of erosion.

Continental believed that the coatings would provide satisfactory erosion protection if properly applied, but with the maintenance hangar environment this would be difficult to achieve, particularly under tight schedules. Both Continental and Delta found that field repair by recommended procedures was unsatisfactory and that simplified repair procedures would greatly increase acceptance of the coatings by airlines.

Flight tests were conducted on the NASA Boeing 737 to measure section profile drag on a coated inboard left wing. Application of CAAPCO from the leading edge to the rear span resulted in a reduction of about 1.4 percent in section profile drag. An extrapolation to total drag on the test airplane at cruise came to a decrease in drag of about 0.2 percent.

With all the test results in, Boeing found that elastomeric polyurethane coatings provide effective protection against leading-edge erosion if properly applied to a clean surface with epoxy primer. Potential drag reduction results when coatings give a smooth leading edge, wing, and tail area. More extensive application will be a function of the price of fuel and the corrosion protection benefits

Model illustrates manner in which a natural laminar flow transport of the future might have its surfaces treated (rust-colored portions).



that would result. The Boeing/ACEE surface coatings program has revealed a very simple, accessible method for saving fuel that can be pursued rapidly.

ACTIVE CONTROLS

Computers are taking on ever-increasing importance in fuel economy. Perhaps the most straightforward application has been integrated energy management. There have been tests that allow the computer instead of the pilot to make decisions about handling the throttles, adjusting power to optimum fuel economy settings at various points in the flight profile. The results showed a 5 percent fuel savings but a 12 percent increase in the time for the trip; thus, decisions on the extent of the program were deferred.

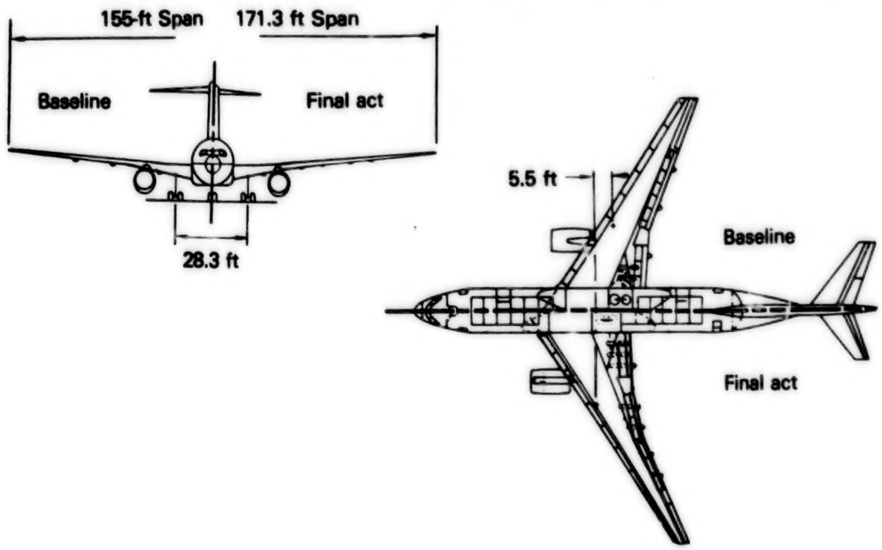
NASA research into active controls is, for the most part, tied to computers and their ability to operate without failing. There is a major difference in concept between active controls and conventional controls. The latter are manipulated by the pilot to move the aircraft from one attitude to another. The pilot makes it turn, climb, or descend by applying the appropriate force to the cockpit control yoke. The aerodynamic surface controls (rudder, elevators, ailerons) deflect the airstream and create forces that turn the airplane about its center of gravity in the desired direction.

Active controls operate independently of the pilot, in addition to whatever command he may be giving. Their motion is intended to generate stabilizing forces to keep the airplane from doing something: bouncing around in turbulence, fluttering at high speed, straining the wing in a tight turn, or oscillating about a desired flight attitude. This automated quick responsiveness reduces stress on the airframe, making it possible to design and construct a lighter, more efficient airplane.

The concept of active control systems predates the oil crisis of 1974, having been a part of the ATT program. In earlier concepts, active controls were seen as a way of reducing the physical size of the horizontal and vertical tail surfaces, thereby reducing drag and aircraft empty weight.

Outside NASA, military and the commercial airlines have been pursuing active controls. Both seek smoother rides for their aircraft and longer life for their airframes. Much of the credit for early flight research work goes to the Air Force for a series of programs that stemmed from a major change in tactics. When the Air Force decided it had to make low-level approaches to targets to escape detection by enemy radar, it had to cope with a new set of problems imposed by flying fast at minimum altitudes. Low-level turbulence hammered the aircraft, disoriented the crew, and strained the airframe. On commercial aircraft, it is almost impossible to avoid turbulence.

Aircraft normally are designed to be statically stable. They will return to their normal straight-and-level flight path when disturbed by a gust or a control input due to the stabilizing effect of their horizontal and vertical tails and the dihedral of their wings. The designer measures this stability in terms of a static



Configuration comparison shows the difference between a conventional baseline transport on one side of each figure and an active controls technology transport design on the opposite side. The wing, control surfaces, and stabilizers are smaller on the latter, reflecting less need for static stability and resulting in less weight and less drag.

margin: a percentage of the wing chord which represents the distance between the airplane's center of gravity and wing's aerodynamic center, where its forces are assumed to be concentrated.

Relaxing the static stability requirements for a high-performance aircraft would require that the airplane be flown all the time by some system that augmented stability. Relaxed static stability is included in active controls research, along with flutter suppression and maneuvering loads.

Any aircraft responds to local turbulence in the air, riding the unsteady winds in an uneven pattern. Sometimes it seems to plow through, with the only evidence of turbulence being light, quick thumps that slightly jar the airplane and its occupants. At other times it rolls, pitches and yaws, or does all at once in an amplified response to the atmospheric turbulence.

The turbulence pattern is completely random; there is no discernible design to its peaks and valleys that a pilot can anticipate and counter by moving the controls. If a sensor were mounted on a boom just ahead of the airplane's nose, connected through a complex analysis and control system to the rudder, elevators, and ailerons, the system would feel and correct for the turbulence. The analyzer would determine its components and strength, and the control system could translate the data into a corrective control motion to moderate the effect of the turbulence. All this would take place in a tiny fraction of a second, far faster than any human could sense and react. The Air Force has flown such test systems in fatigue damage control and ride control.

Active controls can be used to augment the inherent stability of an aircraft, particularly when that inherent stability is low or has been defined by relaxed requirements. Sensors detect deviations from a stable flight path and transmit their readings to a stability augmentation system that controls rudder, elevator, and aileron movements. The artificial, or augmented, stability thus provided can meet all the needs for stable flight, even though it is not inherent in the aircraft. Such active control systems have been developed and tested and are in daily use.

Maneuvering imposes another set of loads on an aircraft. Instead of being the simple, symmetrical loads of level flight, they are unsymmetrical and multiplied, depending on the severity of the maneuver. Those off-center loads increase wing bending in a nonuniform way. That in turn influences wing weight, because wing bending is the important factor in designing the spanwise structure to accept that load as well as others. Reduced wing bending moments mean lighter wing structure and a more efficient aircraft. Consequently, NASA has been studying a maneuver load control system that automatically deflects the wing trailing-edge flaps to change lift distribution and reduce wing bending moments.

An aircraft wing structure is, by its very nature, flexible. It bends to relieve its stresses gently, almost imperceptibly, except in severe turbulence. But the wing has a limit—if the aircraft were flown fast enough, or maneuvered violently enough, the wing might respond by fluttering, vibrating in a pattern that could become so divergent and so severe as to tear the wing right off the fuselage.

Flutter traditionally has been controlled by distributing stiffness to make the wing structurally resistant to the aerodynamic loads that trigger the flutter phenomenon. The active control approach uses sets of auxiliary control surfaces, moved automatically to counter the load conditions causing flutter and, in effect, to increase the aerodynamic stiffness of the wing. That decreases the tendency toward flutter and offers the possibility of reducing the structural stiffening required, which would reduce the structural weight of the airplane.

In recent years, the realm of high-speed flight at high altitudes has made the achievement of simple aerodynamic stability very difficult to maintain over the entire flight envelope. Consequently, stability augmentation systems have taken over parts of the problem and currently are in common use on commercial transports.

The design of such systems calls for redundancy; if one set of stability augmentors should fail, there must be another one to take over. Multiple, redundant systems are the rule for safety, which produces a weight penalty for the airframe. This cannot be avoided due to the limited reliability of contemporary components.

COMPUTERS

Future stability augmentation systems, or other uses of active control technology, will employ a different approach to reliability. They will seek the

very highest level of reliability for all components in the system, with less dependence on multiple systems with lower levels of reliability. These systems will be built, in all likelihood, around a central computer which will process the incoming data from sensors and translate it into commands to the various active control surfaces. Obviously, such a vital organ as the computer must be highly tolerant of faults in the system; if any occur, it must be able to detect, analyze, and compensate for them.

NASA has been evaluating and developing an advanced centralized computer system which continuously monitors all flight control functions, navigation, flight management systems, and displays and evaluates them during flight. If a failure occurs in the system, the computer will identify the faulty processor or memory unit and correct it by reassigning the task to another system or systems. It is possible, then, to lose a single unit of the system, but to receive its information content from other displays or processors, so that flight is in no way compromised through lack of pertinent information.

The prediction is that computers will break down less often than the wings will fall off an aircraft in flight. However, if a "flight critical" computer does fail on a reduced stability aircraft, the net result will be the same, since the aircraft will not be controllable. The lack of confidence in analysis and design techniques and the lack of reliable, cost-effective implementation techniques have been major drawbacks.

An important facet of ACEE active control work is a series of tradeoff studies leading to a better definition of optimum flight control systems. A tradeoff looks at all sides of the problem, starting, generally, with the realization that a system can be improved. It needs updating here, a little more accuracy there, perhaps a lighter component or a better display there. However, the newest gadgets are more expensive. Accuracy also costs money, as does lightness and the improved display; thus, the new and improved system will cost more. Can that cost be justified in terms of the performance improvement increment it produces? These are the types of questions that form the base of tradeoff studies.

FLIGHT TESTING

Once the systems have been put through "breadboard" evaluation, without concern for developing a flight-worthy system, flight testing follows; NASA has advanced to flight testing with a BQM-43 Firebee II drone. For integrated application of aerodynamics, structures, and controls, a joint Langley/Dryden program fitted the BQM-43 with a series of modified wings, including one with a high aspect ratio supercritical airfoil incorporating active controls.

The first tests of active controls on the drone were made using a small research wing with an aspect ratio of 6.8, designed for operation at Mach .92. Its active control system was used for flutter suppression. Tiny, rapid-response control surfaces mounted at the wing trailing edge were actuated to dampen flutter by increasing the aerodynamic stiffness of the wing.

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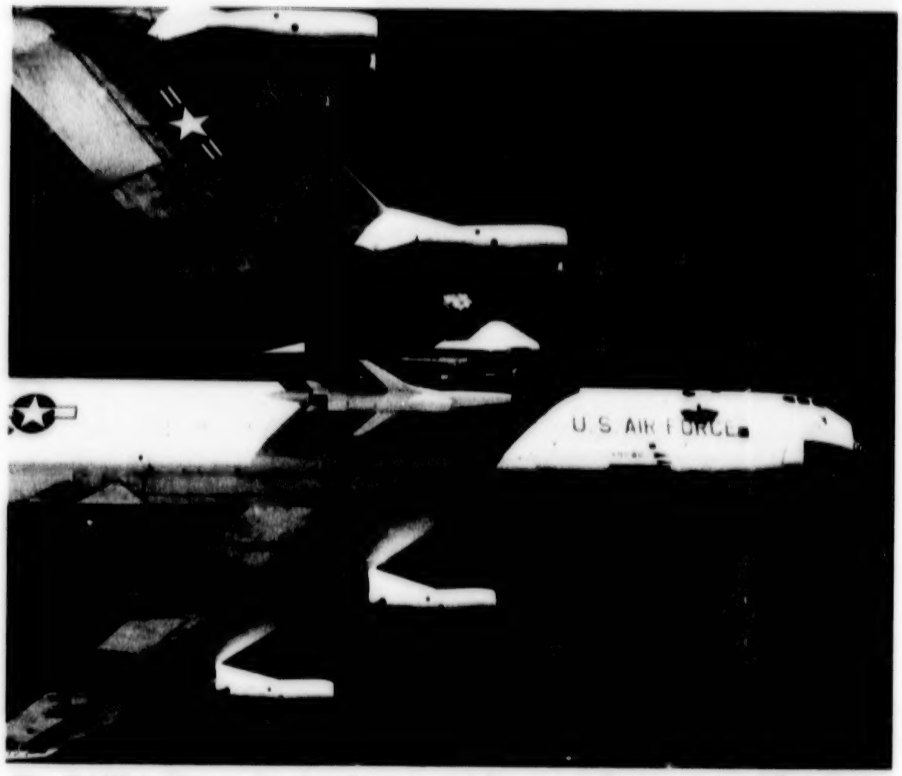

The DAST-1 (Drones for Aerodynamic and Structural Testing), a modified Firebee drone, drops away after release from the B-52A. The supercritical wing on the DAST-1 has an active control system to suppress high-speed wing flutter. The tiny aircraft is guided from the ground.

The second research wing for active control tests is typical of an energy-efficient transport, with an aspect ratio of 10.3. It incorporates active controls to alter the distribution of wing loads and to moderate them to improve both wing structure life and flight safety. This program, Drone for Aerodynamic and Structural Testing (DAST) will yield the first realistic evaluation of wings designed from the outset around the concept of an active control system.

INDUSTRY

The major aircraft companies involved in the active controls portion of EET are Douglas, Boeing, and Lockheed. Each was assigned an area to work on, according to the company's goals and future projects.

Douglas concentrated on relaxed static stability as applied to a future DC-X-200, with a ground rule that the configuration not depend on the system for flight safety. Minimum safe flying criteria for the unaugmented DC-X-200 were

established and evaluated on a piloted motion-base simulator. Several candidate systems were developed, along with suitable controls laws, and were evaluated in terms of availability, reliability, maintainability, cost, and growth capability. The system showing most promise was to be further evaluated, but Douglas has concentrated more on other areas of the EET program. A potential 2.8 percent fuel savings was found for the configuration, along with satisfactory reliability and safety criteria.

Boeing put a heavy emphasis on active controls from the beginning due to research on the forthcoming 767 and 757 with digital computer systems. The company was tasked to investigate the application of wingtip winglets/extensions in conjunction with wing load alleviation to the 747, and toward achieving maximum benefits of active controls, through Integrated Application of Active Controls (IAAC) Technology to an advanced subsonic transport.

After dropping the 747 winglet program, Boeing started IAAC in earnest. The concept was to develop a new baseline transport design without active controls and then redesign to integrate active controls with an eye toward testing the system on the 757. The assessment was to be not only technical, but also economic, based on an estimate of the return on the incremental investment required to acquire an active controls technology (ACT) airplane as compared to the investment for a conventional airplane with the same basic technology.

The conventional baseline transport carried approximately 200 passengers over a design range of just under 2,000 nautical miles with a takeoff gross weight of 270,000 pounds. The wing had an aspect ratio of 8.7, swept 31.5 degrees. The initial ACT configuration incorporated several changes from the baseline. Unaugmented airframe longitudinal stability was eliminated, allowing a 10 percent further aft center-of-gravity range and a 45 percent smaller horizontal tail, with dependence on an angle-of-attack limiting system and pitch-augmented stability system. The wing was shifted forward approximately 66 inches. The wing platform was identical to that of the baseline aircraft, but it was structurally different because of wing-load alleviation.

The final ACT configuration was based on an aspect ratio of 12 and a 31.5 degree wing sweep. The change gave a small reduction to the takeoff gross weight and to the empty weight to reduce the range to the 1,938 nautical miles of the baseline aircraft.

The initial ACT configuration exhibited just over 6 percent improvement in relative fuel efficiency with the same wing shape; the final ACT aircraft, with a 10 percent increase in wing span, produced about a 10 percent increase in relative fuel efficiency. One notable effect was that the improved lift/drag of both the initial ACT and final ACT allowed them to step climb to a more efficient cruise altitude earlier in the cruise mission.

As for the economics of the new aircraft, figured on a 500-nautical-mile mission, the initial ACT airplane would require an incremental investment of $300 000 per airplane and the final ACT airplane $600 000 per airplane relative to the conventional baseline. This translates into enough savings relative to fuel to

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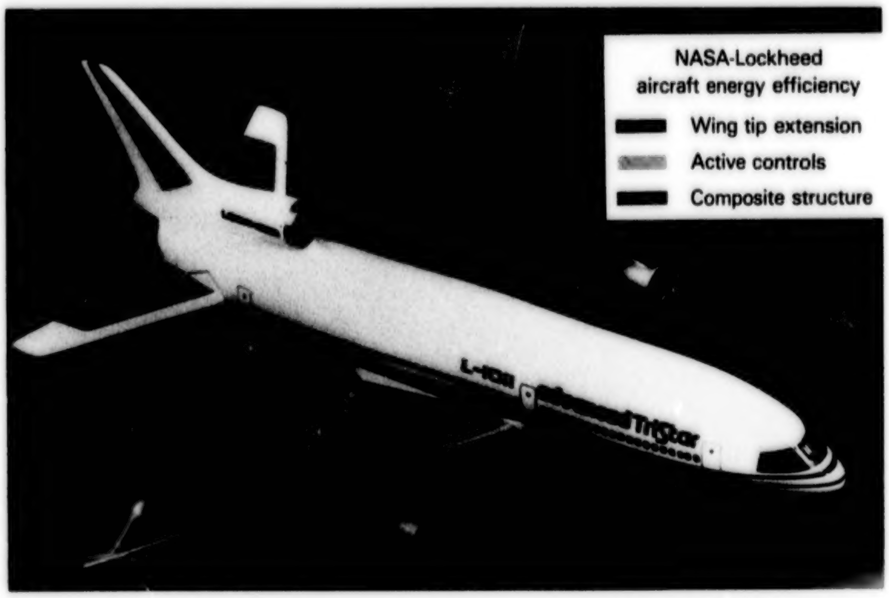
achieve a 31 percent return on incremental investment for the initial ACT and a 25 percent return on the final aircraft, making the additional investment worthwhile.

The technical risks, of course, are the achievement of highly reliable system performance for flight safety and an accurate aerodynamic loads data base for wing load alleviation surfaces. Common mode failures must not cause large transients, and the minimum stabilization and control functions must survive. Motivation is high to produce such reliability when 10 percent block fuel can be saved while realizing a 25 percent return on investment and a payback period of less than two years.

The challenge is to achieve system reliability with a probability of failure of less than 10^9 per flight while meeting the FAA airworthiness requirements that no single failure, regardless of probability, will cause loss of control. The 757 has been chosen for flight test demonstration, and the leap forward in active controls technology is eagerly awaited. Responses were received from several manufacturers of flight control equipment, and a contract has been awarded to begin a joint program to develop controls laws, hardware, and software leading to delivery of a set of flight control electronics for ground test.

Until the early 1980s, Lockheed put most of its EET program emphasis on active controls. In conjunction with wingtip extensions on the L-1011, their ACT work has centered on maneuver-load control, elastic mode suppression, and gust alleviation.

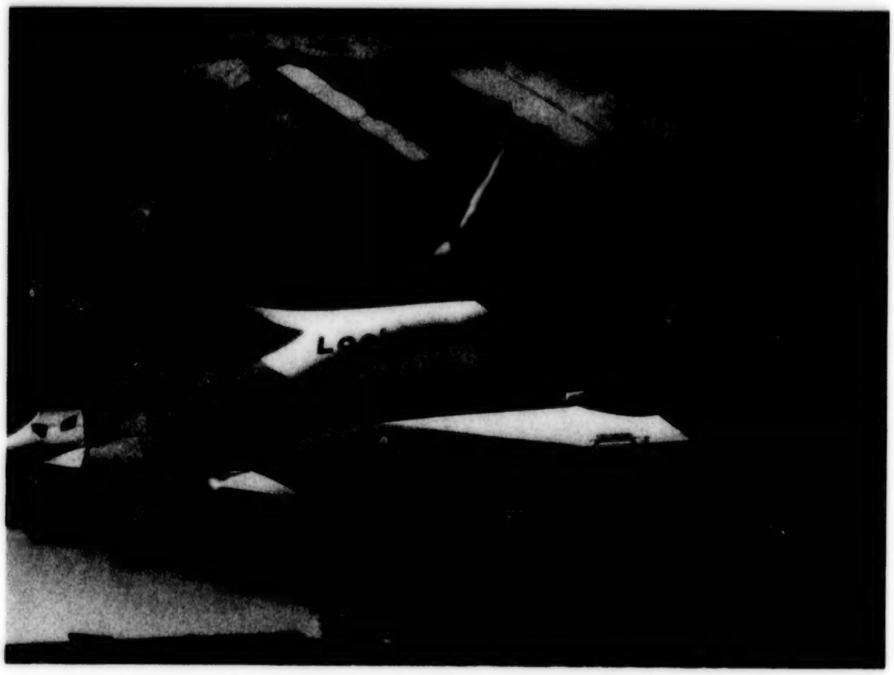


Lockheed took the ACEE ACT research and decided to apply it to the next generation of L-1011 transports by using wingtip extensions, active controls, and composite structures.

The active control system, developed in-house by Lockheed with company funds, uses maneuver-load control through automated flap deflections to redistribute the lift during turning flight. The NASA/ACEE contract greatly accelerated the ACT work, leading to 4.5-foot span extensions on each wing without any major beefing up of the wing structure due to the installation of the active controls. Specific range tests resulted in a gain of 3 percent in fuel efficiency. Excellent results with the system led to basic certification of the controls for the FAA and the airlines.

Lockheed next conducted flight simulation tests to verify the ACT flying qualities and make use of ACT concepts to fly with the center-of-gravity further aft than normally permitted, resulting in less drag. The results were encouraging, with no control reversals, resulting in the use of both outboard and inboard ailerons at high speeds. The reliability of the system proved high, although that was not sought.

By 1980 a production version of the Advanced TriStar was offered in the L-1011-500 with the span extension and ACT system. Pan American Airlines bought the first aircraft with active controls, and the improvements have been retrofitted on all the -500s flying. The big hurdle of establishing the credibility of this new technology with the FAA and the airlines had been overcome.



The Advanced TriStar prototype was modified under NASA contract, and wingtip extensions were mounted.

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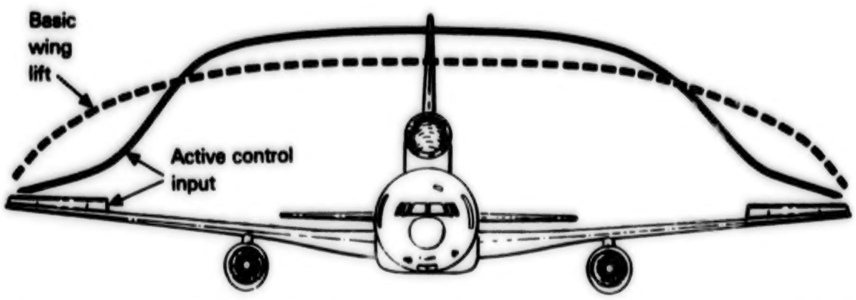
In the next phase of EET, Lockheed decided to keep its focus narrow and concentrate on demonstrating technology for achieving relaxed static stability on a current widebody aircraft, the L-1011, with active controls. The first area to explore was reducing the size of the tail while maintaining the same stability margins; exploration of relaxed static stability margins to recapture trim drag losses would follow.

With the initial design work on a supercritical airfoil on the horizontal tail, the 3 percent improvement in drag did not show up. With NASA help, a new airfoil was designed that resulted in 10 percent static instability with an advanced supercritical wing and an 11 percent improvement in drag. However, the small tail was abandoned due to the high cost of full-scale testing. All effort was subsequently put into demonstrating the ability of active controls to offset reduced static stability margins with good results that could find their way into near-term aircraft modifications. The initial theory is to pump fuel from other parts of the aircraft into the rear fuselage in flight, shifting the center of gravity.

Lockheed has identified three phases for further work. Existing avionics can be modified quickly to obtain new control laws using the ailerons or the tail, although they will not be used together due to the need for coupling research. Fixed ballast or water ballast can be used to verify the handling and stability of an aft center-of-gravity aircraft, and a competitive procurement was approved for a new or modified computer. Supercritical airfoils are also being studied in more depth.

Flight control concepts for the 1990s are being examined, leading to new approaches to control theory and new control laws. A total fly-by-wire transport has yet to be produced, although military aircraft like the F-16 have proven the production possibilities. Aerodynamic improvements on control laws, through the use of canards, is being studied for transports, but with cruise efficiency the



Theoretical lift distribution over the wing of a transport in level, unaccelerated flight (dashed line). Active controls, which respond to the varying conditions of flight that produce accelerations and therefore change the airload distribution, alter the cruise load distribution to a more favorable pattern (solid line). The reduction of load at the wingtips and the shift of the major load to the wing roots means that the wingtip structure can be built more lightly to the required strength and that the wing root accepts the extra load where it can be handled most efficiently.

main criteria, the aerodynamic interference effects are still a problem. For the present, Lockheed has been happy to apply ACT results in the near term on the L-1011, with significant results.

The EET portion of ACEE has produced a body of advanced technology with a potential for application that could result in fuel savings of up to 20 percent, yet the participants in the program feel that it has only just begun.

Chapter 7
Laminar Flow Control

Today's civil air transports typically cruise at about 500 miles per hour. One problem in traveling this fast occurs within the boundary layer, a thin region of air between the free air stream and the surfaces of the wings, fuselage, and tail of an airplane. Under some flight conditions, this layer closely follows the aircraft contours and is smooth, a condition referred to as laminar flow. Under other conditions, the boundary layer flow changes from laminar to turbulent, creating drag that wastes fuel.

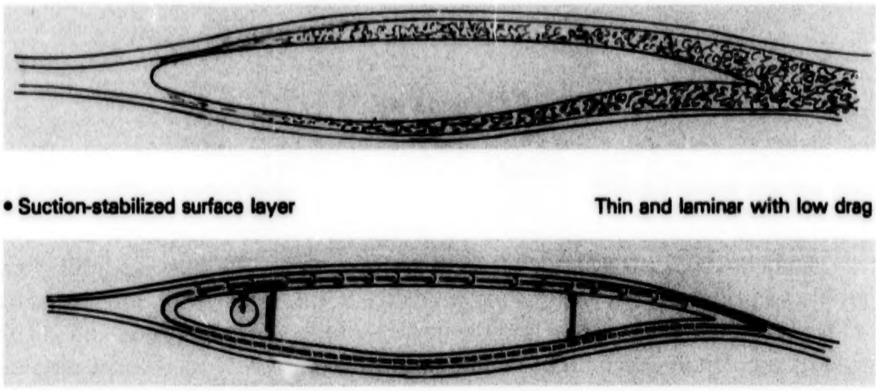
Laminar flow control provides the greatest potential for fuel conservation, from 20 to 40 percent savings, depending on the extent of application and the airplane's design range. The concept, however, would require a radical change in aircraft construction, calling for removal of the turbulent boundary layer by suction, thus maintaining laminar flow. Suction requires development of porous or slotted aircraft surfaces and lightweight pumping systems.

An understanding of laminar flow and its history is essential to visualizing the work that the NASA ACEE program is doing in this area. When a fluid moves past a solid surface, a thin layer of the fluid (air) develops adjacent to the surface, where frictional forces tend to retard the motion of the fluid. This boundary layer generally exists in one of three states: laminar, in which fluid particles travel along well-ordered nonintersecting paths; transitional, in which disturbances become amplified, causing the smooth "layered" flow to become disrupted, with some mixing of particles between layers; and turbulent, in which fluid particles from adjacent layers become totally mixed.

The state of the boundary layer is directly related to the relative speed and the distance the fluid has traveled along the surface. Transition of the boundary layer from laminar to turbulent results from selective amplification of disturbances that exist in the fluid stream itself or disturbances generated by irregularities and imperfections in the surface.

It has been demonstrated that the growth of these disturbances can be controlled and that a turbulent fluid state can be prevented by removing a small amount of fluid in the boundary layer—Laminar Flow Control (LFC).

Associated with the transition of the boundary layer from laminar to turbulent is a large increase in the frictional force between the fluid (the air) and the aircraft surface, called viscous or friction drag. On commercial aircraft now in use, the boundary layer is virtually always turbulent. During cruise, about half



A normal airfoil creates enough airflow boundary layer turbulence to generate a significant amount of drag. With laminar flow control suction applied to the surface, the boundary layer is stabilized, resulting in lower drag. Potential fuel savings of up to 20 percent have warranted investigating a practical solution to this complex problem.

the engine power needed to maintain level flight is required to overcome the turbulent friction drag. Because about 70 percent of the fuel used on a transcontinental trip is consumed during cruise, reducing the friction drag can offer significant potential for fuel consumption.

Research on LFC predates World War II. In the late 1940s, Great Britain, using captured German LFC studies, conducted successful wind tunnel experiments followed by flight tests on Anson and Vampire aircraft, with continuous suction resulting in laminar flow being achieved. The United States successfully flew an F-94 LFC glove, but it was not until the early 1960s that Northrop, under a U.S. Air Force contract, built a full LFC testbed, the X-21A aircraft. Two WB-66Ds, converted to X-21A standards, were modified with a slotted suction surface LFC system for the wing, and the aerodynamic feasibility of the concept was demonstrated. With the growing heat of the Vietnam War, the program was cancelled, and industry concerns about the economics and maintainability of LFC were not answered.

Providing the required surface suction is complicated by the need to vary this suction over different parts of the wing using a single pump. Dust, mud, and even smashed insects can cause disturbances that negate the suction effect over an area large enough to be a drawback. Materials and structural arrangements compatible with suction requirements have limited practical application of LFC as well. Only recently have structural concepts (combined with lightweight, strong, and rigid materials) been developed that could bring LFC systems closer to reality.

For the most part, LFC research was dormant from 1964 until 1976, when NASA included it in the ACEE program. Because of the potential benefits of

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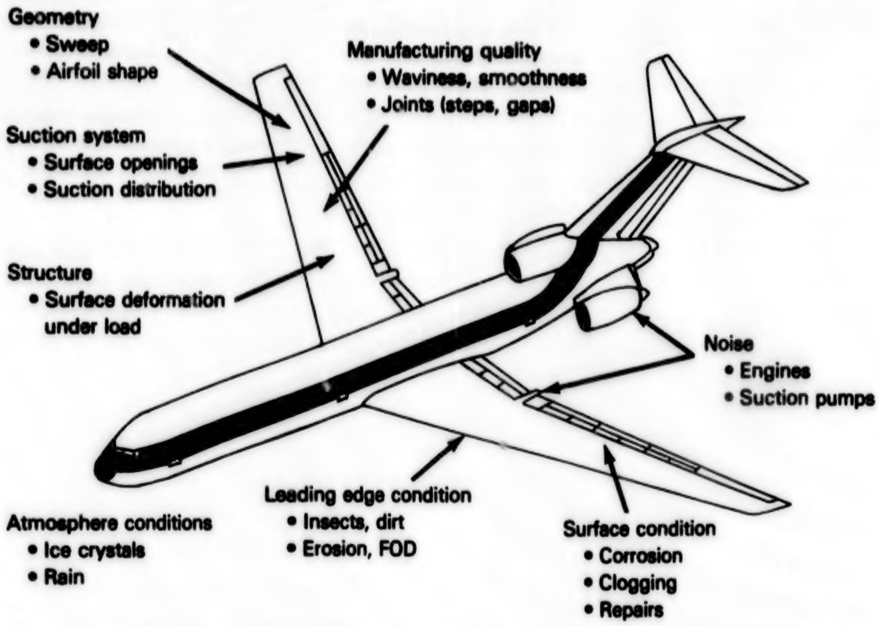

Many factors affect laminar flow, as shown here. Reducing these to the point of producing a practical piece of hardware is the challenge facing engineers and designers. ACEE took a big step forward in performing much of the necessary research.

LFC research and the increasing cost of fuel, NASA felt it was time to reenter this area to the point of flight testing actual systems.

With the start of the ACEE program, LFC research was broken down into the following areas: wing geometry, such as sweep and airfoil shape, that will be compatible with LFC and also maintain the advantages of supercritical flow; manufacturing processes that can economically produce structures with the necessary stringent controls on waviness, joints, and gaps; proper suction distribution and the best surface configuration to achieve it with minimum corrosion and clogging problems in the airline operational environment; and systems and operating procedures that will prevent the sensitive laminar boundary layer from being triggered into a turbulent state by bugs, other contaminants, or noise.

INDUSTRY

Boeing, Douglas, and Lockheed were put under NASA contract to conduct extensive preliminary design of potential configurations, structural concepts, and suction system approaches. The work included breadboard systems tests, wind tunnel tests of wing sections that incorporated candidate suction systems, laboratory tests of slotted and porous wing surface concepts, construction and

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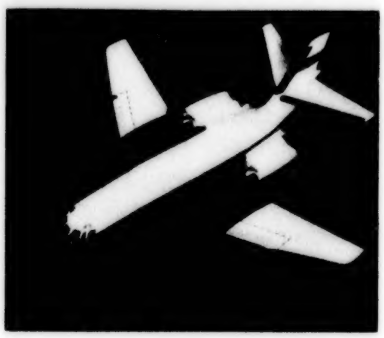
test of fabrication of feasibility specimens, and evaluation of leading-edge cleansing concepts.

Boeing designed a 550-nautical-mile-range, 200-passenger aircraft with three rear-mounted engines; Douglas designed a 5,000-nautical-mile-range, 300-passenger aircraft with four rear-mounted engines; and Lockheed designed a 6,500-nautical-mile-range, 400-passenger transport with four rear-mounted engines; all as possible LFC designs of the 1990s.

Advanced airfoil development results defined a supercritical shock-free airfoil with a small leading-edge radius designed to reduce undesirable spanwise flow. Friction drag was reduced 85 percent, with performance comparable to advanced turbulent airfoils; a wide range of shock-free conditions was achieved; a

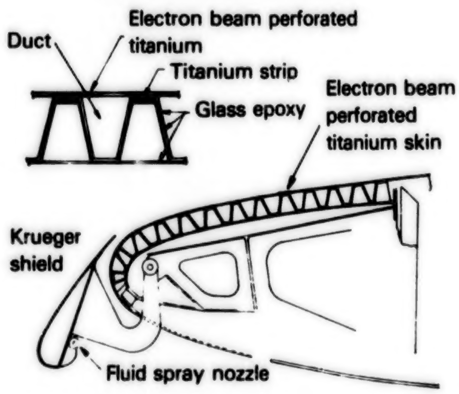
JETSTAR LEFT CONFIGURATION



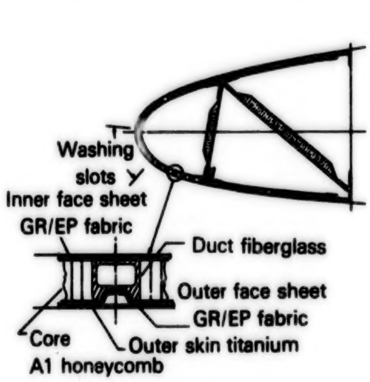
OBJECTIVE

Demonstrate effectiveness of leading edge systems to maintain laminar flow under representative flight conditions

DOUGLAS TEST ARTICLE



LOCKHEED TEST ARTICLE



Lockheed and Douglas have developed leading edge LFC test articles for flight research using different approaches to the problem. Douglas proposes a Krueger shield with fluid spray that can be retracted once above most of the potential impact area and an electron-beam perforated titanium wing surface. Lockheed wants to fly a spanwise slot system with washing slots to clear the leading edge. Both have great promise, and most of the hardware has been built.

trim flap was found effective for pressure distribution control; and leading-edge stagnation line suction was found unnecessary.

Much of the LFC aerodynamic study was done by computerized analysis. Computer codes were developed to accomplish this. An existing transonic wing code and a modified boundary layer code were integrated to provide the analysis capability to define wing surface pressure distributions and boundary layer characteristics with an LFC system. Another code that described boundary layer stability led to knowledge of the wing suction flow that would be required to maintain laminar flow over a desired wing design.

AIRFOILS AND SURFACES

The advanced supercritical shockless airfoil itself has an unusual shape when compared to more conventional airfoils. The upper surface is a smooth, large-radius arc, rounding into a leading edge. The lower surface is concave near both leading and trailing edges, and convex between. The prototype wing section tested in NASA wind tunnels had a 7-foot chord, a 23 degree sweep, and a 13.1 percent thickness ratio. It was equipped with full-span suction slots on both upper and lower surfaces and tested at Mach numbers between .8 and .9. Following the slotted model work, additional tests were conducted on an electron-beam perforated titanium porous surface. This enabled a comparison of slotted and porous surface measurements.

All three companies took part in aerodynamic evaluation of the possible LFC airfoils. Boeing conducted low-speed tests on a 20-foot-chord model with a slotted suction surface and a 30-degree swept leading edge. Douglas performed low-speed tests on a 6-foot-chord model with a porous suction surface and a 30-degree swept leading edge, and Lockheed made transonic tests on a 7-inch-chord model with a nonporous surface.

Douglas' porous outer surface layer was a departure from the slotted concept, with some distinct advantages. First, it was easy to manufacture due to electron-beam perforation on the titanium. It had greater tolerance to two-dimensional disturbances—local suction blockage did not cause transition. Minor damage was simply repaired, it was more tolerant of off-design conditions, and the pore distribution allowed ideal suction to be approached. Simple steam cleaning was found to clean pore blockage quickly.

Lockheed, using the older slotted suction approach, found LFC feasible as well. They found it environmentally acceptable in the presence of lightning strike, corrosion, icing, and low temperatures. Foreign object damage was a problem only at the slot, which was repairable with hand tools. Using a thick graphite-epoxy structure, Lockheed engineers were able to meet existing gap, shape, and step tolerances that demonstrated manufacturing feasibility.

A number of suction-power options were evaluated, including dedicated suction power units, suction pumps using the main propulsion engines and a

bleed air-burn cycle, and the suction pump sharing an auxiliary power unit with other systems.

Surface roughness, particularly due to insect residues after takeoff and landing, is a potentially serious problem for LFC aircraft. A successful solution to this problem would remove a major element of risk for the practical application of LFC. Program participants believe that the leading edge is the key research area and that if the major problem is solved, the remaining LFC problems are solvable. If the LFC apparatus on a transport wing failed entirely, the airfoil would have to perform well enough to bring the aircraft home.

Nonadhering surface materials, particularly Teflon, offer LFC promise, as well as maintaining uncontaminated surfaces through washers, mechanical shields, or subliming materials.

TESTING

Leading-edge contamination flight tests were made on the NASA JetStar with the deicer boot off and a new leading edge with four or five wing skin panels varying from highly polished aluminum to Teflon. The ultraslick, water-shedding panels were flown with and without in-flight washing from a system of water spray nozzles mounted underneath the leading edge of the wing. It was found that the washing system was needed because bugs would stick to the surfaces, tripping the boundary layer. Although the test surfaces did not prove to be very beneficial, the effectiveness of a liquid film was demonstrated.

In wind tunnel tests by Douglas, a leading-edge high-lift Krueger insect shield proved effective as a line-of-sight barrier for heavy insects, although a supplemental liquid film system was needed for some areas. A leading-edge fluid cleaning system was tested by Lockheed in the wind tunnel, and it was found that slots were more effective than porous or perforated surfaces in dispersing the liquid.

In 1978, due to other program resource demands, Boeing suspended work on the LFC effort while Lockheed and Douglas pressed on toward preparation for flight tests of their LFC wing surface panel concepts. Both companies built a spanwise section of a wing leading edge to test for laminarization, de-icing, and insect protection. Mounted as gloves on the wings of the NASA JetStar, a direct comparison of the slotted and perforated approaches will be available while providing operational experience on ice particle effects, foreign object damage, erosion, and clogging/cleaning requirements. Future planning for the LFC program will depend largely on the outcome of these tests.

As an alternate approach, Boeing has studied hybrid laminar flow control. A combination of LFC and natural laminar flow, this approach combines the best features of both through the use of suction LFC ahead of the front spar, followed by natural laminar flow run further aft on the chord where cross-flow

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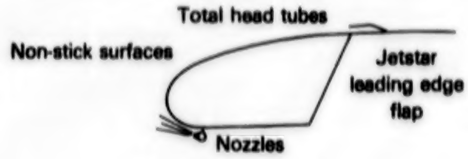


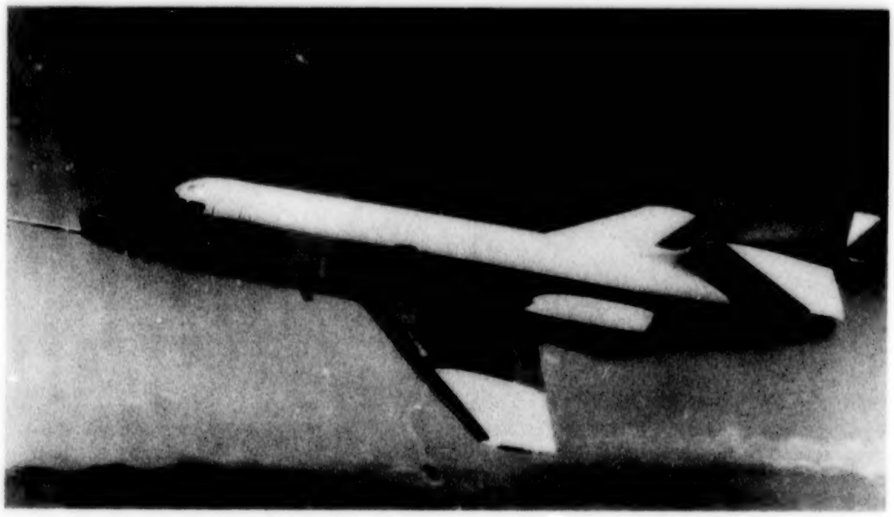
Criteria
- Laminar flow behind prepared surfaces
- Post-flight measurement of excrescence heights

Surface treatments
- "Non-stick" and hydrophobic coatings
- Compare to bare aluminum

Deposit erosion
- Cruise mach no., altitude, temperature

Washer
- In combination with coatings
- Operation during impact vs. in-flight cleaning
- Type and quantity of fluid required

Many researchers believe that if the leading edge contamination problem can be solved, the remaining laminar flow challenges will not be as difficult to solve. In the ACEE Leading Edge Contamination Flight Test, a leading edge washing system was applied to a superslick surface to remove bugs and dirt while helping to prevent erosion of the surface.



An artist's impression of the NASA JetStar with an LFC test article attached to the wing.

disturbances are less pronounced. A significant lift/drag increase is expected at conventional sweep without the complexity of suction control over the wing box. Boeing has discussed testing the system in a wind tunnel, leading to possible flight evaluation on the 757. For the upper surface, 40 percent laminar flow over the inboard region and more than 60 percent over the outboard region appears to be attainable.

LARGE-SCALE TESTING

Hopes persist for demonstrating an LFC wing on a production aircraft in the mid to late 1980s. It would be a major and costly undertaking to design and fabricate production hardware. Integration of surfaces, ducting, substructure, and systems would have to take place, along with fabrication methods and tooling for production hardware. Douglas performed a feasibility study of a DC-9 LFC validator that would simulate airline service. Realistic operating economics and drag-reduction data could be obtained from this aircraft, along with experience with systems maintenance, inspection, and repair.

Because the concept functions best at high altitudes, the benefits are most attractive during the cruise portion of the flight profiles. The greatest payoff will therefore be on long-range (2500 to 5000 nautical mile) missions, but the DC-9 could provide practical LFC test hardware, leading to possible use of the technology in airline service by the year 2000.

The reduction in direct operating costs made possible by LFC has stimulated airline interest, and as the program has advanced—and fuel prices have continued to soar—interest has become more serious. Funding for continued research remains in question.

Douglas

5000 n. mi. range
300 passengers

Lockheed

6500 n. mi. range
400 passengers

Douglas and Lockheed concepts for long-range LFC transports.

Chapter 8
The Future

The aviation industry's net positive contribution to the nation's foreign trade balance was $13.3 billion in 1980, exceeding any other industry sector, including agriculture, while employing 1.3 million people. That American lead is now being eroded by foreign competition, particularly by the Aerospatiale Airbus, which is built with a substantial subsidy from the French Government. Since 1978 the United States has been outsold 3 to 1 in worldwide competition among foreign air carriers. Other foreign governments, including Japan, are putting increasing amounts of money into advanced commercial transport research to exploit this foothold in the marketplace.

The Japanese have had singular success in wresting other areas from U.S. dominance in the world market—one has but to think of the automobile and electronics industries. In each case a financially strong American industry is courting financial disaster as a result of lost technological superiority and cannot now compete with the highly subsidized products of other nations.

The U.S. aviation industry is a national resource, and much of its success can be attributed to the unique role that research and technology has played. Since 1916 NASA and its predecessor NACA has helped develop a strong technology base, which, coupled with industry's ability to efficiently apply technology, have provided the foundation for America's steady rise to leadership in world aviation.

Fuel economy is another side of the same coin. Certainly conservation of fuel will add tremendous cost savings to commercial and military aviation, and that goal is worthy in itself. But for the United States to survive in the world market, it must have for sale products that save more fuel than those of the competition. Those aircraft that are the most efficient, while keeping maintenance and procurement costs in line, will grab the market.

To these twin goals the NASA ACEE program has been dedicated—to retain America's place in world aviation and to provide the best fuel economy.

The first six years of the ACEE program have paved the way for dramatic results in the coming years. Much time and effort have been devoted to gathering data and information in many unknown areas. Although there have been very substantive short-term results, particularly in ECI, much work must be done to exploit the potential for fuel savings uncovered in ACEE.

The original committee that produced the ACEE program intentionally identified the highest-risk technologies with the highest potential yield so that

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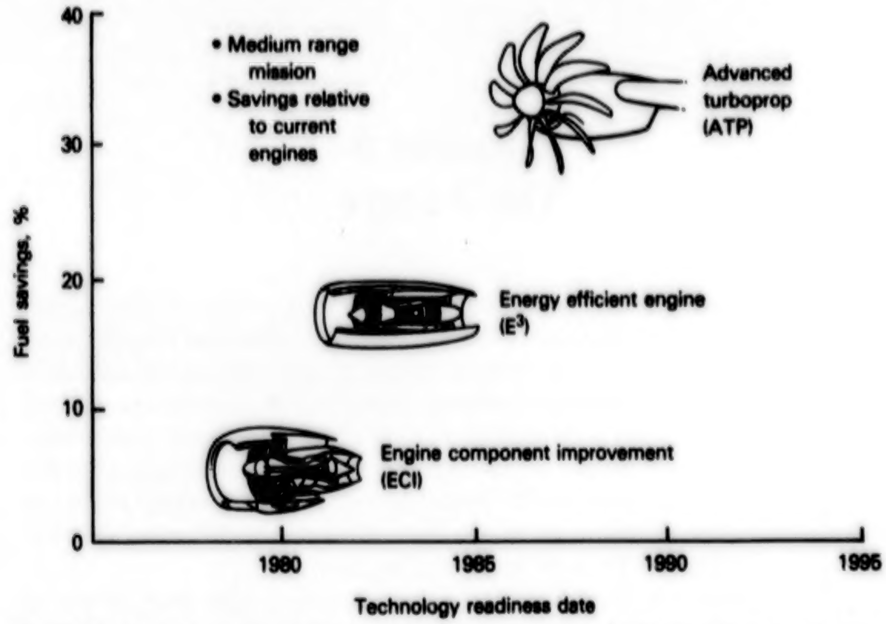

Should the ACEE program continue as originally outlined, the three propulsion systems can be in the marketplace at these approximate dates, saving the percentage of fuel shown. ECI is already completed and saving fuel.

NASA could aid industry in working on them, fully aware that individual firms could not afford to reach so far into the future. Each program was planned with a test article at the end so that the concepts could be proven in the real world. Failure to proceed with such demonstrations could leave the technology unexploited.

Arguments against further NASA involvement have revolved around the concept that companies should be involved in their own research and development, taking all the risk themselves. Companies should be profitable enough to do this alone, but since 1974 the economy has not been kind enough. NASA stepped in to help reach forward. In the eyes of many, visionaries must be protected because 20- to 30-year lead times are not unusual from the beginning of a major future concept to its realization in the marketplace. The NACA charter was written for just such a reason.

ACCOMPLISHMENTS

So far the major accomplishments of the ACEE program have centered around three areas: composite structures, practical active controls, and engine component improvement.

The first is the introduction of intermediate primary composite structures into transport design—lighter, stronger, and more efficient to manufacture, they

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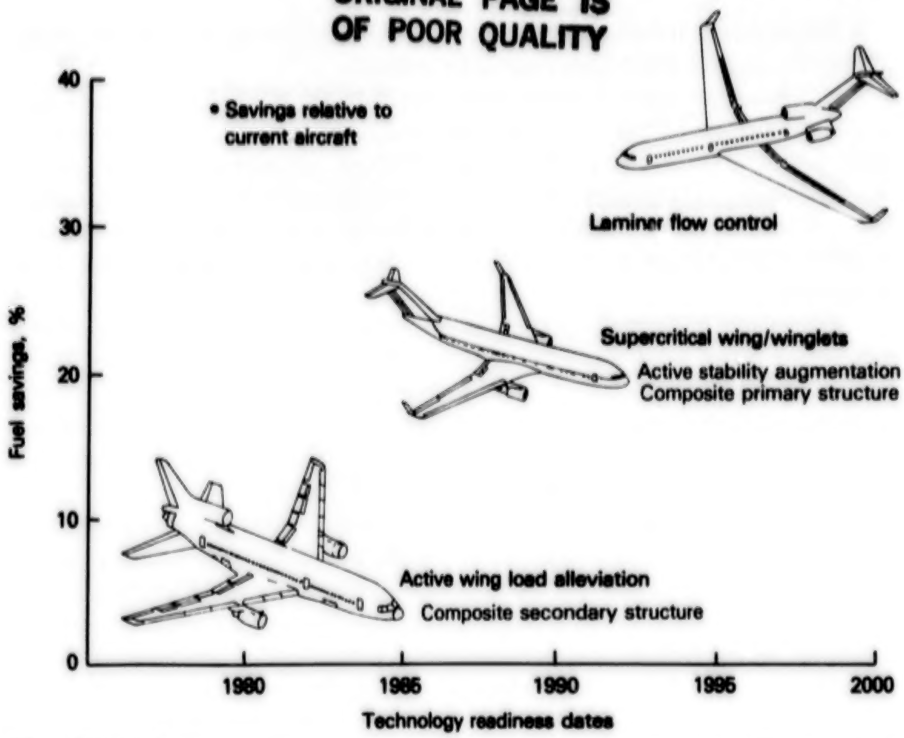

The ACEE airframe programs are equally far reaching in their potential effects on fuel savings and the balance of trade.

mean less fuel burned, better aerodynamic efficiency, and simplified construction techniques. Aircraft are flying with new materials that will take the place of aluminum. Designers are visualizing new structures incorporating composites and built with composite-dictated techniques in mind rather than just putting composites on aluminum aircraft. This leap will be as dramatic as that from wood and fabric to aluminum, requiring major investments on the part of industry. NASA help has been pivotal in providing the seed money to investigate the transition to composites.

The second major accomplishment is practical active controls that reduce fuel consumption, provide a smoother ride, and enhance aerodynamic efficiency. The ability to produce an active control gust alleviation system and investigate relaxed stability requirements has put manufacturers directly into new design criteria for transport aircraft. That the gust alleviation system has proven practical enough for production is a major step.

The third achievement is fuel savings that are being realized now, not at some time in the future, through the ECI program. With the many small payoffs in improving engine performance a reality, these components are flying in current production engines and saving a great deal of fuel, setting the pace for future turbofan engine technology.

Regardless of the present benefits from the ACEE program, the full potential of the areas investigated is yet to be realized.

Laminar flow control, the concept with the greatest potential fuel savings, is also the hardest to reach and the most costly to research. Companies are not likely to invest funds in a concept without in-flight hardware trials. Yet, due to its very nature, LFC is often the hardest to envision because it is pushing against the limits of our current technology. NASA's head start on solving the problems involved will need continuing support or the potential may slip away and never be realized.

The advanced turboprop is another concept that offers substantial future fuel savings yet is testing the limits of our ability to provide it. Much remains to be done to make it a system that goes beyond a new propeller. New engines and airframe technology must be developed in concert. Flight tests are crucial to seeing how a large-scale system will work. Yet, with so much yet to be proven, no company will risk the investment without NASA's help.

The technology base provided by ACEE will be extremely important not only to the commercial transports of the future, but to the Department of Defense, which has conducted little research similar to the six program areas of ACEE because it has relied on ACEE to provide the research base. This is not unusual, since NASA has always been strong in researching military aeronautics. According to Lt. Gen. Lawrence A. Skantze, Commander of the U.S. Air Force Aeronautical Systems Division, "The ACEE Program is complementary to Air Force programs and we have followed the progress of this NASA program with great interest. The research efforts of NASA are a major contributor to the technical data base for Air Force systems of the future. NASA research efforts influenced our planned research and development and significantly improved the advanced technology applied to systems. The technology demonstrations associated with their programs are necessary if new concepts are to be incorporated by aircraft designers."

The Department of Defense has been particularly desirous of investigating future application of advanced aerodynamics, active controls, composite structures, and the propfan, as well as laminar flow control.

The serendipity of ACEE is that it can benefit the future aircraft of both the military and commercial sectors. The impact on the future United States balance of payments should more than offset the R&D expense, although much still has to find its way into industry application after continued research.

About the Author

Jeff Ethell, a certified instructor pilot and commercial pilot, is author of more than 14 aviation books and a well known free lance writer for numerous aviation magazines including Air Force Magazine, Air Progress, Air Classics, and Business and Commercial Aviation. He is a member of the American Aviation Historical Society and the Warbirds Division of the Experimental Aircraft Association. In addition to being an experienced pilot of such World War II aircraft as the P-51 Mustang and the B-25 Mitchell, Ethell has logged several hundred hours in modern military jet aircraft.

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